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A COMPARATIVE ANALYSIS OF FUTURE SPACE ORBITAL TRANSPORTATION SYSTEMS

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THESIS

A COMPARATIVE ANALYSIS OF FUTURE SPACE ORBITAL TRANSPORTATION SYSTEMS

by

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June 2018

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This thesis conducts a comparative analysis of future Orbital Transportation Systems (OTS). Near future rocket advancements are compared to future capabilities of a well-documented non–rocket based OTS, the space elevator transportation system. Technical and geopolitical impacts of both systems to future space exploration and the space industry are analyzed. Recent multiple new entrants into the space rocket industry are developing larger payload capacity rockets and driving down the cost per kg to orbit. These advances will lead to major improvements in the way spacecraft and satellite engineers will design their future systems with fewer payload constraints and lower total mission cost constraints. While beneficial, these advancements in rockets could have an adverse effect on the continuing efforts to develop alternate OTSs, such as the space elevator, by reducing the research and design (R&D) funding available for those systems. A space elevator offers the promise of consistent daily to-orbit transportation with a very large payload capacity at an extremely inexpensive cost. For these reasons, the space elevator system is worth the continued R&D investment to address major technical challenges in its continued development.

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A COMPARATIVE ANALYSIS OF FUTURE SPACE ORBITAL TRANSPORTATION SYSTEMS

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ABSTRACT

This thesis conducts a comparative analysis of future Orbital Transportation Systems (OTS). Near future rocket advancements are compared to future capabilities of a well-documented non–rocket based OTS, the space elevator transportation system. Technical and geopolitical impacts of both systems to future space exploration and the space industry are analyzed. Recent multiple new entrants into the space rocket industry are developing larger payload capacity rockets and driving down the cost per kg to orbit. These advances will lead to major improvements in the way spacecraft and satellite engineers will design their future systems with fewer payload constraints and lower total mission cost constraints. While beneficial, these advancements in rockets could have an adverse effect on the continuing efforts to develop alternate OTSs, such as the space elevator, by reducing the research and design (R&D) funding available for those systems. A space elevator offers the promise of consistent daily to-orbit transportation with a very large payload capacity at an extremely inexpensive cost. For these reasons, the space elevator system is worth the continued R&D investment to address major technical challenges in its continued development.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEHF	Advanced Extra High Frequency
CNT	carbon nanotube
DoD	Department of Defense
EELV	Evolved Expendable Launch Vehicle
GPa	GigaPascals
INCOSE	International Council of Systems Engineers
ISEC	International Space Elevator Consortium
ISS	International Space Station
ITS	Interplanetary Transportation System (SpaceX Mars proposed Rocket)
kg	kilogram
MILSTAR	Military Strategic and Tactical Relay
MOP	measure of performance
MT	metric tons
NPS	Naval Postgraduate School
OTS	Orbital Transportation System
R&D	research and development
SE	systems engineering
SLS	Space Launch System (NASA's latest heavy lift rocket-based transportation system)
TRL	Technology Readiness Level
U.S.	United States
ULA	United Launch Alliance (joint venture rocket company of Boeing and Lockheed Martin)
USD	United States Dollars

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EXECUTIVE SUMMARY

Recent new entrants into the space rocket industry have forced innovations to happen faster than the traditional government/large corporation controlled industry has been accustomed to in the past 60 or so years. Additionally, a revitalized interest in the human population becoming a space-faring species, traveling to near future locations like to the Moon and Mars, have helped focus more attention on non-rocket–based transportation systems to orbit. This has helped continue to increase payload capacities of rocket-based systems and continued to drive down the cost per kg to orbit. These, in turn, make the likelihood that humans will travel to and establish extra-planetary outposts and later on habitations more possible in this century.

This thesis investigates the future of these Orbital Transportation Systems (OTS) and compares near future rocket-based capabilities with the space elevator transportation system. The concluding results of this analysis are as follows:

1. Utilizing a systems engineering process, measures of performance (MOPs) were developed to compare two OTSs: near future rockets to a leading non-rocket OTS, the space elevator. Near future rockets have the competitive advantage over the space elevator in five of the seven MOPs identified. However, both systems have unique characteristics and capabilities and depending on the requirements of a mission, one system could be preferred over the other.

2. New major entrants into the rocket industry will continue to push an increase in payload capacity and decrease the cost per kg to orbit of near future rockets systems (within the next five to 10 years). This will in turn evolve into an upward spiral of continued growth in the space industry, which will appear as if it is only in its infancy today as near as 20 years from now (~2037).

3. The increase in payload capacity and cost per kg to orbit will impact the way space system engineers and scientists design their systems to take advantage of these transportation system improvements in the future. Space industries like the Satellite Communications (SATCOM) industry will benefit in the following ways:

   i) SATCOM engineers will design satellite structures to support the systems necessary to meet mission requirements, rather than optimize and adapt satellite systems to fit a structure compatible

with the size of a launch vehicle and the rigors of a launch sequence.

ii) Larger satellites, delivered by a larger payload capacity rocket or space elevator, would provide increased physical structure to mount a greater number of antennas, providing maximum gain for numerous individual frequencies or narrower frequency bands. Additionally, large aperture optical and radar systems would benefit greatly from increased payload capacity.

iii) Larger satellite vehicle structures will also provide space for larger power generation, power storage, and power management systems, to include power amplifiers.

iv) New satellites could incorporate advanced on-board digital processing hardware, firmware, and software, to facilitate on-orbit processing, ensure secure, high-speed communications, and provide flexibility in communication systems via on-orbit network management.

v) The SATCOM industry would benefit from the democratization of satellite communication, satellites with capability and capacity similar to ground stations.

vi) Larger payload capacities will allow systems that are currently on the drawing board or in laboratory experiments, such as space-based solar power, to begin to make sense economically and from a space construction standpoint.

vii) Interplanetary ships could now be conceived to be built or assembled in orbit, with higher payload capabilities and lower costs per kg to orbit.

4. The space elevator, the major non-rocket OTS alternative, appears to be technically feasible, with the assumption that tensile strength in materials, such as carbon nanotubes (CNT) continue down the development path they are currently progressing. This system could be technically achievable as early as the mid-2030s.

5. The practice of rigorous systems engineering (SE) is applied in the space industry. In the development of the space elevator system in particular, SE has been applied in developing an extremely well thought out plan and program to continue down the development road and address all major technical hurdles and challenges with a systematic approach.

6. Technical advantages of non-rocket OTSs like the space elevator make it quite an appealing system to continue to develop. It has advantages, such as:

i) A comparison of payload capacity “throughput” to orbit would indicate a space elevator system would be able to transport more payload to orbit then traditional rockets, unless significantly more launch infrastructure was developed.

ii) A space elevator would offer the unique capability to be able to transport systems back from space to the earth.

iii) The unique capability space elevator could offer is the ability to work on systems in space, at one of its space gates. Systems would begin to be designed in a completely different way, to take advantage of this fact.

7. Geopolitical challenges are being overcome in the United States to allow major new entrants into the rocket industry, which will continue to drive up rocket capability and drive down costs per kg to orbit.

8. Geopolitical challenges with developing a space elevator system will be quite daunting, as the major challenge will come with locating the earth port of the system and facing the challenges associated with operating and protecting an evolutionary gateway to space.

The future for rocket-based systems looks very bright for the near term as multiple new-entrants continue to develop larger payload capacity rockets and continue to "compete" for (mainly SATCOM) business, thus driving down the cost per kg to orbit. This could have an adverse effect on continuing to develop alternate OTSs, such as the space elevator, as R&D funding that could be available for those systems gets swallowed up by new missions that could be accomplished with the larger payload/lower cost of new rockets. However, from a physics perspective, the rocket-based system is, and unless some breakthrough new fuel-source is discovered, tied to the fate of the Rocket-Equation; one cannot simply ignore the rules and laws of Newtonian Physics. This limitation, and a consistent daily orbital shuttle of very large payload capacity at extremely inexpensive costs, makes the space elevator system (and other alternatives to rockets) worth the R&D dollars to continue to push the challenges related to such systems to move the low technology readiness level (TRL) areas up the TRL ladder.

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Above all, the author would like to dedicate this thesis to his creator, who has provided air to breathe, water to drink, the means for which to acquire food, and the ability to reason; these precious gifts shall not be wasted.

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I. INTRODUCTION

Continued advancements in both rocket-based transportation systems (i.e., reusable rocket system advancements and larger payloads as found in SpaceX's recent achievements) and continuing advancements in the materials science of high strength to density materials (such as carbon nanotubes [CNT]) are on the verge of considerably reducing the cost and dramatically increasing the payload capacity of transporting systems to space. The latest estimates to these advances indicate rocket-based systems that are currently in development could offer a payload capacity of 8–300 metric tons (MT) per rocket launch at an estimated cost of \$140–\$28,000 per kilogram (kg) (SpaceX n.d.a.; Kyle 2017; Musk 2017). Additional non-rocket advances in orbital transportation concepts, such as a space elevator indicate the cost to travel to geostationary orbit (GEO) and beyond could be reduced even further to \$50–\$500 per kg, and payload capacities are estimated at 14–79 MT per Space Elevator Transportation Tether Climber (i.e., per lift) (Swan et al. 2013). This thesis performs a systems engineering analysis of these near future options, focusing on the potential technical and geopolitical impacts of such revolutionary advances of "to-orbit" transportation systems to the space industry, and compares latest estimates of future rocket-based systems to a future leading non-rocket orbital transportation concept: a space elevator system.

A. THESIS OBJECTIVES

This thesis has two objectives. These are:

1. To compare advantages and disadvantages of advanced orbital transportation systems, such as projected future rocket-based systems to space elevator transportation systems.

2. To investigate the technical and geopolitical impacts of advanced orbital transportation systems to the space industry and the DoD.

B. THESIS METHODOLOGY

The methodology approach taken to this thesis is an analytical research method, applying systems engineering skills and thinking to this topic. The steps taken to develop the overall plan for the research and analyses conducted in this thesis are as follows:

1. Conducted literature research to determine what alternatives there are available and worthy to conduct comparative analysis.

2. Narrowed focus on one alternative concept that from research appeared to be most developed (space elevator).

3. Utilized INCOSE *SE Handbook*, Technical Processes (INCOSE 2015, ch. 4) to help frame "problem" and potential solutions, with the "problem" being defined as the comparison of near future rockets to non-rocket Orbital Transportation Systems OTSs.

4. Utilized NASA's Risk Management Handbook (National Aeronautics and Space Administration Headquarters 2011) to perform an Objective's Hierarchy analysis to identify measures of performance (MOPs) to be used in the comparative analysis.

5. Developed scenario-analyses to help in the comparison of the alternatives and MOPs.

6. Compiled additional advantages and disadvantages of alternatives based on research, not specifically related to the developed MOPs.

7. Developed conclusions, recommendations, and further research based on the steps outlined earlier.

The steps listed above allowed the author to break down the fundamental attributes of current rocket-based OTSs and consider what alternatives have been proposed and studied in the literature. The author focused on a comparative analysis comparing near future rocket-based systems with a leading non-rocket based system; comparing the effectiveness of the two systems to transport spacecraft to and from orbit.

C. BENEFITS OF THE STUDY

The primary benefit to study future advances to OTSs is the opportunity to step back and take a systems engineering approach in first defining the problem of getting space systems into orbit, instead of focusing on the continued advancement of one potential solution. Since the beginning of the space era in the mid-1900s, and recent commercial interests in further developing rocket-based transportation systems is focused on developing only one solution to getting space systems into orbit: through the use of rocket-based transportation systems. Taking a step back, allows for the comparison of current and near future projected rocket-based systems to one of the leading non-rocket based transportation system, the space elevator concept. Utilizing systems engineering (SE) skills will help frame the problem and compare different solutions.

D. THESIS ROADMAP

This opening chapter has presented the initial conception, motivation, and objectives of this thesis. Chapter II focuses on the systems engineering tools and techniques used to further develop the thesis objectives into a defined problem, identification of stakeholders, and exploration of solution space, ultimately developing MOPs derived from an objectives hierarchy decomposition, to be used to compare the two system alternatives. Chapter II also includes a short discussion on the literature search done on both rocket-based and non-rocket based OTSs. Chapter III further documents the capabilities and shortcomings of both alternative solutions to the problem. Chapter IV builds upon Chapters II and III by conducting the comparative analysis of the two systems. Chapter V is an extension of Chapter IV and discusses the technical and geopolitical impacts of both system alternatives. Finally, Chapter VI offers conclusions and recommendations.

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II. DEVELOPING PROBLEM STATEMENT

One of the main challenges associated with developing a solution for a complex problem is defining the problem accurately enough to ensure the solution meets the major objectives and requirements of the problem trying to be solved. This chapter focuses on the systems engineering (SE) steps taken to define the problem and narrow down the solution space to be analyzed. The first step was to conduct a literature search of the topic of interest to "bound" the thesis topic. SE tools were then applied to define the problem, identify and characterize the solution space, and develop alternative solutions to be analyzed.

A. LITERATURE RESEARCH

To begin the thesis research, the author conducted literature research to determine and refine the thesis objectives and thesis methodology. The literature research focused on the following topics:

1. Past, present, and near future rocket capabilities, including new entrants into the industry and their promises and claims on their future capabilities.
2. Non-rocket based OTSs and ultimately narrowed the focus onto what appears to be the leading concept, the space elevator.
3. The space elevator concept, specifically its promises for future capability and the current roadblocks holding this concept from becoming a reality.
4. General research on SE methodology applied to OTSs to determine what studies have been done focusing on problem of getting into orbit, rather than focusing on one solution.

The results of the literature research are referenced throughout the thesis and included in the reference section at the end of this thesis. The major sources of reference material include:

- research paper publications from multiple aerospace, aeronautic professional associations;
- official papers and books from government agencies (i.e., NASA);

- websites and research papers from major companies involved in the space industry (i.e., SpaceX, Lockheed Martin); and
- multiple third party websites (news media) focused on the space industry.

Topics 1 through 3 above resulted in the list of references at the end of this thesis. Additionally, topic 4 is further discussed as applying SE thinking to this subject was of great interest.

Over the past two decades, the major contributors to researching topics like the space elevator concept are for the most part system thinkers and systems engineers. Research into this aspect of the space elevator reveals this is the case. Table 1 lists major SE reports and papers developed since 2003 on the space elevator concept. Nevertheless, applying some current SE to this system and possibly updating and/or introducing new concepts has been taken on as a part of this thesis, as discussed earlier in this chapter.

Table 1. Historical Systems Engineering Efforts Applied to Space Elevator Concept

Report Title	Report Material Description	Date Published	Reference
Systems Engineering for the Space Elevator—Complexity	Report takes an SE approach to identifying major complex areas of a space elevator and establish a methodology to lower risks/address issues.	2003	(Pullum and Swan 2003)
Handling the effects of Complexity in Space Elevator Requirements	Paper proposes two models as communication tools to facilitate requirements development and overall management of Space Elevator concept.	2004	(Giorcelli and Pullum 2004)
The Space Elevator: A revolutionary Earth-to-space transportation system	Major research effort (NASA NIAC Funded). Study organized using Systems Engineering Thinking.	2003	(Edwards and Westling 2003)
Space Elevator Concept of Operations	Major effort discusses various operational concepts for space elevator	2012	(Penny, Swan, and Swan 2012)
Space Elevators: An Assessment of the Technological Feasibility and the Way Forward	Major research effort (published thru International Academy of Astronautics). Study organized using Systems Engineering Thinking.	2013	(Swan et al. 2013)
Space Elevator Architectures and Roadmaps	Major effort discusses major architectural concepts of space elevator and roadmaps to developing each subsystem.	2015	(Fitzgerald et al. 2015)

B. PROBLEM STATEMENT DEVELOPMENT

As mentioned in the previous chapter, a comparative analysis comparing two alternatives to providing orbital transportation is the focus of this thesis. Before performing the comparative analysis, some systems engineering (SE) techniques are applied to 1) identify the major stakeholders, 2) define the problem or opportunity space, 3) characterize the solution space, and 4) establish performance criteria to compare both alternatives. Steps 1, 2, and 3 are based upon the methodology contained in the International Council of Systems Engineers (INCOSE) 2015 *Systems Engineering Handbook* (INCOSE 2015). In the handbook, Chapter 4 identifies 14 technical processes for applying SE to a problem. The technical processes highlighted in the INCOSE *Systems Engineering Handbook* Chapter 4 are included in Appendix A. For this thesis, the first technical process (Business or Mission Analysis) was performed to analyze an

Orbital Transport System to help define the problem and identify alternate solutions to the problem. The major steps associated with the first technical process are to

1. nominate major stakeholders
2. define the problem or opportunity space
3. characterize the solution space

C. NOMINATE MAJOR STAKEHOLDERS

For this analysis, research into the topic of Orbital Transportation Systems (OTSs) helped identify the major stakeholders and users that have a major interest or a stake in the only current solution to an OTS, the rocke-based system, as well as major stakeholders that will have an interest in potential alternate solutions to rocket-based transportation systems. The major stakeholders identified for this effort include the major governments of the world that have committed space programs, multi-national entities, some of the major designers and commercial entities involved in the aerospace industry, the rocket industry, and industries with interest in being able to develop systems that will exist in orbit (i.e., telecom and navigation industries). This list has been developed by the author, mainly through research into this topic. The list of entities is shown below, grouped into their major categories:

1. Major governmental entities directly involved in space exploration: NASA (USA), DoD (USA), ESA (Europe), JAXA (Japan), RKA (Russia), Chinese Space Agency (China).
2. Major national/international government funded agencies indirectly involved in space exploration: United Nations, NOAA (USA), EPA (USA).
3. Major commercial companies directly involved in space transportation system development: SpaceX, ULA, Boeing, etc.
4. Major commercial companies identified as users of space transportation systems: Major Telecom companies that use space satellites for communications, major companies that launch GPS satellites, etc.

As identified in the INCOSE handbook, if this were a major system development effort, the next step in a stakeholder analysis would be to query the major stakeholders to understand their wants, desires, and needs of a system solution. Those wants and needs would then be developed into system requirements. For the purpose of this thesis, literature search was used to research the system requirements. This will be discussed in the objectives hierarchy section below.

D. DEFINE THE PROBLEM OR OPPORTUNITY SPACE

After initial research into the topic of space transportation systems and in particular, planned near future advancements and claims by rocket-based transportation systems companies, the author began defining what the opportunity or solution space for an orbital transportation system should look like. As discussed in Chapter I, once a set of thesis objectives were established, the author could begin to narrow down and focus on defining the problem the thesis is going to address. The problem definition and focus of this thesis is stated as:

> To provide inexpensive, safe, reliable, repeatable transportation to orbit (LEO, MEO, GEO and beyond) and/or a more efficient way to address overcoming Earth's gravitational pull to allow for space systems to transport into orbit (LEO, MEO, GEO and beyond).

E. CHARACTERIZE THE SOLUTION SPACE

Once a problem is defined or stated, the next step is to focus on characterizing the potential solution space. Characterizing the solution space, involves describing what the end state of the system should look like and in some situations (as in this case) attempt to extend or enhance existing solutions to the problem. Thinking about current system capabilities and current capability gaps of existing systems can further help define the solution space. The main characteristics that will bound the solution space for this problem will be payload capacity, cost per lift to orbit, and system reliability. A generalized solution space is stated in the following manner:

A system that can deliver large payload capacity (better than existing payload capacities, 20–50 tons, see Chapter III) to and from LEO, MEO, GEO safely at or below today's current cost ($10,000–20,000) per kg, existing cost to orbit, see Chapter III) on a regularly scheduled basis.

A summary of the above three analyses is shown in Table 2.

Table 2. INCOSE Technical Process 4.1 Applied to Orbital Transportation System Process.

4.1	Business or Mission Analysis Process		
	Nominate Major Stakeholders	4.1.2.1	Major governmental entities directly involved in space exploration: NASA (USA), DOD (USA), ESA (Europe), JAXA (Japan), RKA (Russia), Chinese Space Agency (China). Major National/International Government funded agencies indirectly involved in Space exploration: United Nations, NOAA (USA), EPA (USA). Major commercial companies directly involved in space transportation system development: SpaceX, ULA, Boeing. Major commercial companies identified as users of space transportation systems: Major Telecom companies that use space satellites for communications, major companies that launch GPS satellites.
	Define the Problem or Opportunity Space	4.1.1.4.b	Inexpensive, safe, reliable, repeatable transportation to orbit (LEO, MEO, GEO and beyond) and/or a more efficient way to address overcoming Earth's gravitational pull to allow for space systems to transport into orbit (LEO, MEO, GEO, and beyond).
	Characterize the Solution Space	4.1.1.4.c	Deliver Large Payload Capacity (20–50 tons) to and from LEO, MEO, GEO safely at or below today's current cost to LEO ($10,000–20,000 per kg).

F. IDENTIFYING ALTERNATIVE SOLUTION FOR COMPARATIVE ANALYSIS

Once the initial up front work of identifying the major stakeholders (deriving their wants/needs into requirements), defining the problem to solve, and characterizing the solution spaces, the next steps help shape a system concept and architecture that can solve the problem. In the case of this thesis, since there is currently only one solution in existence, the next step involved identifying the next best-conceived alternative to allow for the comparative analysis. The next best alternative was identified through a literature search (further described below). The literature search was clear in identifying the next closest system that could be developed into an OTS is the space elevator system. Once this was identified as the alternative, a method needed to be used to develop MOPs to help compare the two alternate solutions. The MOP development is discussed in the next section.

G. OBJECTIVES HIERARCHY DECOMPOSITION

Another useful SE technique is to develop an objective hierarchy decomposition. A good example of an objectives hierarchy decomposition utilized in this thesis is discussed in Chapter 3 of the *NASA Risk Management Handbook* (National Aeronautics and Space Administration Headquarters 2011). This process and technique allows for top-level objectives to be decomposed to the point where they can be measured and discussed when comparing various alternatives. Once an objective hierarchy decomposition is conducted, the systems engineer can then identify MOPs to help in comparing alternative solutions to the problem. Figure 1 shows objectives hierarchy decomposition for an OTS.

As derived from Figure 1, multiple MOPs were identified to help comparing the two alternate solutions. Two quantitative MOPs identified in Figure 1 and will be used to conduct a use case scenario in Chapter IV are: volume/mass capability to deliver to orbit, and cost to deliver mass/volume to orbit. Additionally, a number of capabilities that are unique to each system alternative are discussed compared as capability differences of the two alternate solutions.

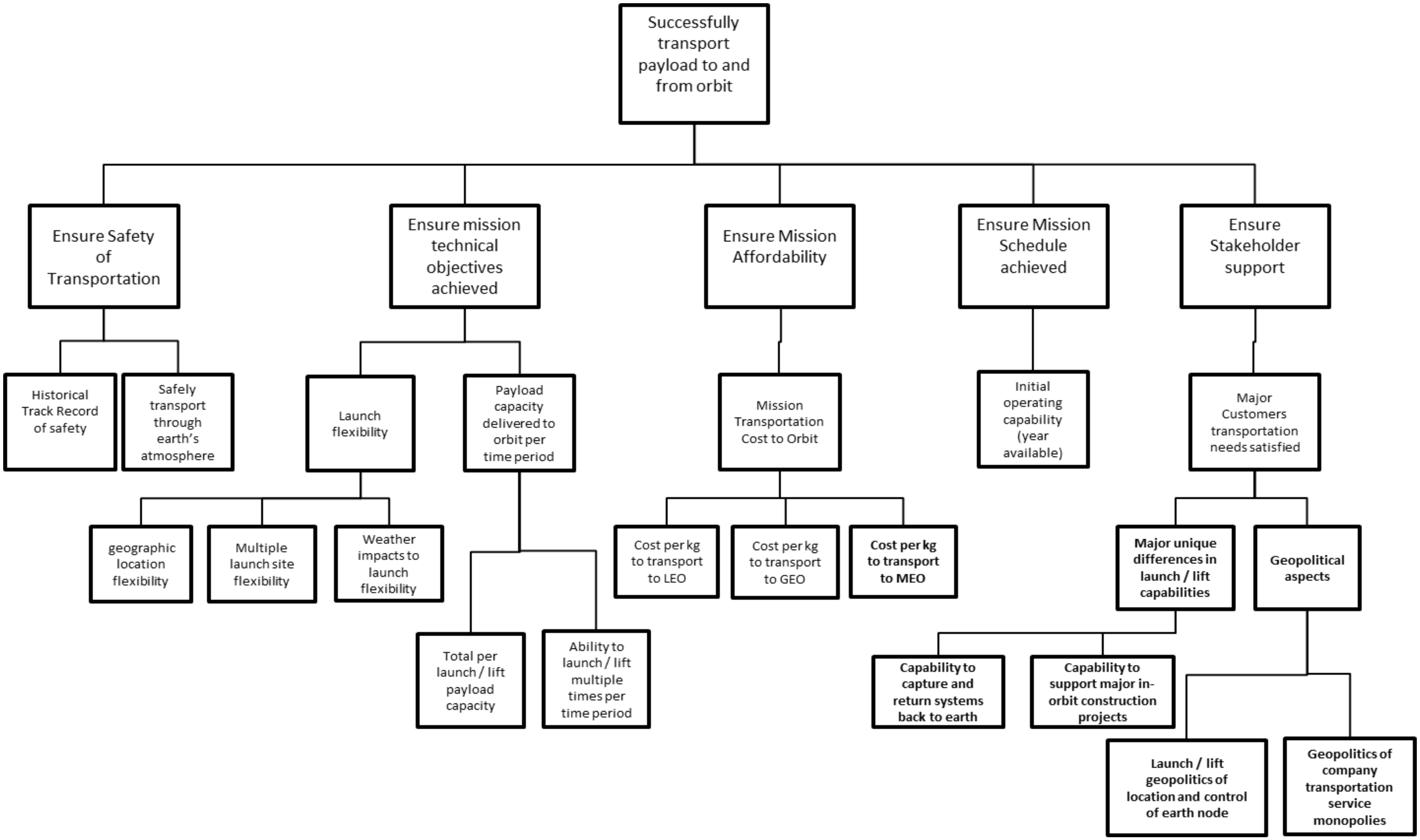

Figure 1. OTS Objectives Hierarchy Decomposition.

H. CHAPTER SUMMARY

This chapter focused on following the systematic process of moving from initial research, to problem definition, to solution space characterization, to alternative solutions to be analyzed. Now that this progression has been made, the alternative solutions have been identified, the next steps moving forward will be to characterize, compare, and analyze the alternative solutions via the MOPs developed in this chapter.

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III. ORBITAL TRANSPORTATION SYSTEMS

This chapter will provide details on the characteristics and capabilities of current and near future orbital transportation system design alternatives. Rocket-based transportation systems will be discussed first followed by non-rocket based alternative systems. Multiple non-rocket based systems will be introduced, then the chapter will focus on the characteristics and capabilities of the space elevator system, the main alternative compared to rocket-based systems in this thesis.

A. ROCKET-BASED TRANSPORT SYSTEMS CAPABILITIES: PAST, PRESENT, AND FUTURE

A revolution of rocket-based transportation systems is ongoing. The introduction of private companies into what historically has been a government-designed system and service has brought about a major inflow of new resources changing and advancing rocket-based transportation systems. This change from the traditional way rockets have been designed and operated, has helped to continue to lower the cost to orbit and increase the payload capacity.

Data was gathered on the historical payload capacity of past, present, and future planned rockets. Table 3 summarizes the latest estimates of technical capabilities of near future rocket-based systems currently in development (Appendix B includes brief summaries of the major corporate players currently developing these systems). Figure 2 shows images of the new major entrants into the rocket-based transportation systems. Figure 2 graphically displays the payload capacity (in terms of Metric Tons delivered to LEO) compared to the rocket’s mean year in service (the data used for Figure 2 was adapted from (Skrabek n.d.) and is shown in tabular format in Appendix B). Table 3, Figures 2 and 3, all indicate that other than a few systems in the early 1970s and one system in the late 1980s, there appears to be a trend in growing payload capacity that is happening for most recent and near future systems. The systems shown in Table 3 are shown in red in Figure 3. The SpaceX ITS system is not shown in Figure 3 as its projected payload capacity is literally off the chart at 300 MT. Indeed, it is an exciting time to be involved in the rocket-based space industry as new non-governmental entrants are testing higher limits of payload capacity, and if the claims in payload capacity and cost to orbit become reality, the ability to lift space systems into orbit to achieve new heights in space exploration will be technically capable.

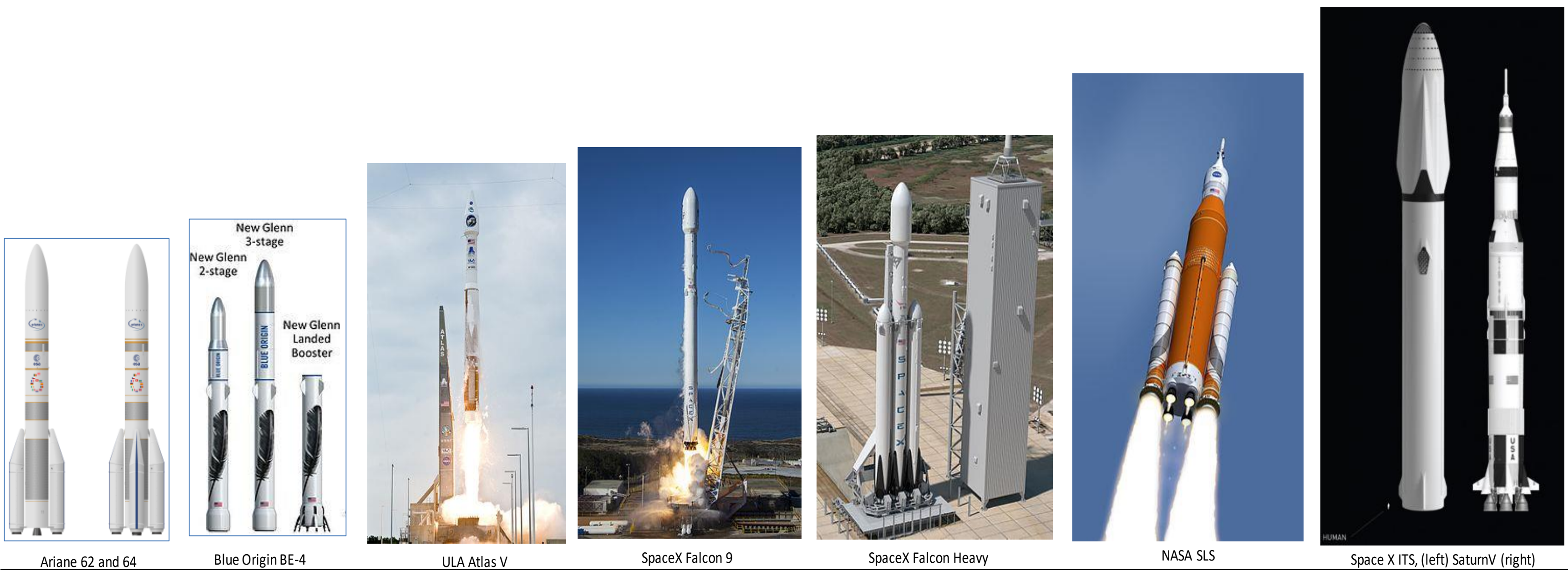
Table 3. Current/Near Future Rocket-based Systems Technical Capabilities. Source: Smith (2016); Berger (2017); SpaceX (n.d.b.); Musk (2017); Kyle (2017).

	Ariane 64 (a)	**Blue Origin BE-4 (b)**	**SpaceX-Falcon 9 (c)**	**SpaceX-Falcon Heavy (c)**	**SpaceX-ITS (d)**	**NASA–SLS Block 1A (e)**	**ULA Atlas V (a)**
Payload Capacity to GEO (MT)	10	13	8.3	26.7	300[i]	17.7–45.4	8
Estimated Cost to GEO ($ USD/kg, see notes)	$13,891–$16,979	No Data	$11,272.73	$11,250	$140[ii]	$20,000–40,000	$27,867.41
Projected Operational Date (year)	2020	2019	Currently operational	2018	2023	2023	Currently operational
Planned Reusability	None planned	plan: 1st stage, up to 100 times	Still testing capability	Still testing capability	see note [iii]	None planned	None planned

Per Reference (a) Cost per kg calculations	Cost	Total Weight to GEO (kg)	Cost per kg To GEO
ULA Atlas V	$225,000,000	8,072	$27,873.10
Ariane 62	$77,000,000	4,535	$16,979.05
Ariane 64	$126,000,000	9,070	$13,891.95
Space X Falcon 9	$62,000,000	5,500	$11,272.73
Space X Falcon Heavy	$90,000,000	8,000	$11,250.00

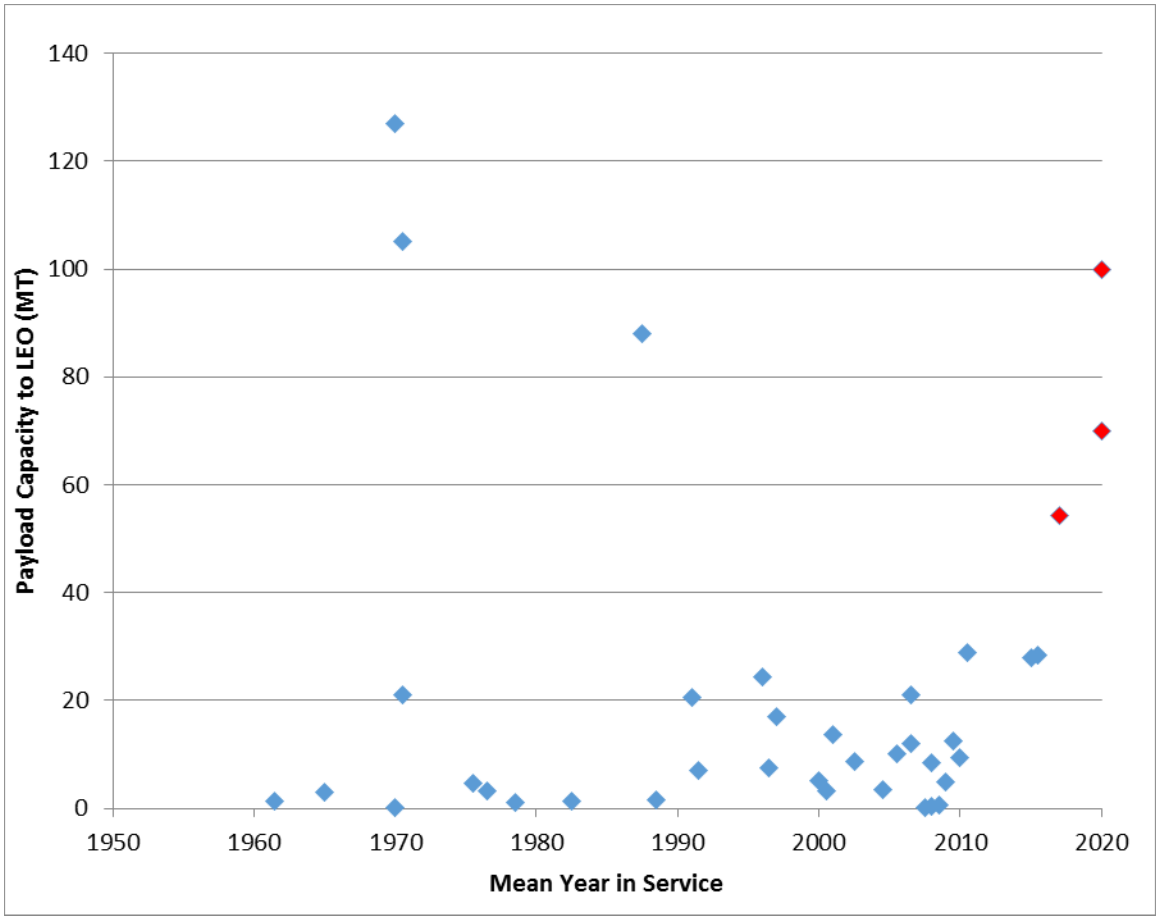
References: (a) (Smith 2016) (b) (Berger 2017) (c) (SpaceX n.d.b.) (d) (Musk 2017) (e) (Kyle 2017)

Notes: (i) fully reusable payload to LEO; (ii) Estimate E. Musk presented as cost per ticket for passenger to travel to Mars; (iii) Targeted reuse per vehicle: 1,000 uses per booster, 100 per tanker, 12 per ship.



Notes for figures: Ariane image: (Wikipedia 2018a); Blue Origin image: (Berger 2017); ULA Atlas V image: (Wikipedia 2018b); SpaceX Falcon 9, Falcon Heavy, and ITS image: (SpaceX n.d.b.); and NASA SLS image: (Kyle 2017)

Figure 2. Rocket Images. Source: Wikipedia (2018a); Berger (2017); Wikipedia (2018b); SpaceX (n.d.b.); Kyle (2017).



Note: Last three markers in red are future systems. Additionally, SpaceX ITS system not shown. Its planned capacity to LEO is 300 MT, and proposed service beginning date is 2024. This data point of 300 MT would be completely off current chart parameters.

Figure 3. Past, Present and Future Rocket Payload Capacity to LEO (in metric tons) vs. Mean Service Year. Adapted from Strabek (n.d.).

B. NON-ROCKET ORBITAL TRANSPORTATION SYSTEMS

The major challenge the Earth's gravitational force, specifically breaking away from its pull, has inspired many different concepts to attempt to develop systems to transport cargo/humans to orbit and beyond. In addition, the challenge the rocket equation presents continues to inspire alternative non-rocket transportation systems. A brief list of these alternative systems is shown in Table 4 (Wikipedia 2018c).

Table 4. Orbital Transportation System Concepts. Adapted from Wikipedia (2018c).

Method (a)	Payload Capacity to GEO (MT)	Estimated Cost to LEO (US$/kg)(b)	Technology Readiness Level
Rockets	700–300,000	$140–40,000	9
Space Elevator	14–79	$50–500	2
Hypersonic skyhook	1.5		2
Hypersonic Airplane Space tether launch	15		2
Orbital Ring	200,000,000	$<0.05	1
Launch Loop	5	$300	1
Star Tram	35	$43	1
Space Gun	0.45	$1,100	3
Slingatron	0.1		2
Orbital Airship		$0.34	3

The space elevator is one such alternate to rocket-based transportation systems. Many other proposals exist shown in Table 4, too many to be able to conduct an in-depth investigation of all of their current feasibility states. The author has chosen to compare the space elevator to rockets, as the space elevator has been the most documented non-rocket transportation system alternative, and appears to be the leading alternative to rocket-based systems. The next section will focus the space elevator system.

C. SPACE ELEVATOR TRANSPORTATION SYSTEM: PAST, PRESENT, AND FUTURE

The space elevator concept has been idealized and researched both in science fiction and in legitimate science and engineering concept studies for more than a century. The novel concept was first introduced by Russian space pioneer Konstantin Tsiokovsky in 1895, and captured in the article by Jerome Pearson titled: “The Real History of the Space Elevator” (Pearson 2006): “Using the Eiffel Tower as a model, he [Tsiokovsky] imagined towers reaching into space, and discovered the balance point at which gravity seems to disappear, which is the synchronous altitude we now commonly refer to as GEO” (Pearson 2006).

Later in the middle of the 20th century, two engineers working completely independent of one another, Yuri Artsutanov and Jerome Pearson, began conducting the first real scientific calculations that a space elevator could conceivably exist, if a material that had the tensile strength to support such a structure were invented. Major follow on studies beginning in the early 2000s by NASA's Institute for Advanced Concepts (NIAC) office confirmed that a space elevator is technically feasible, assuming major advances in high tensile strength material can be made in the future (Marshall Space Flight Center, NASA 2000; Edwards and Westling 2003).

The NASA study and the follow on book by Edwards (2003), spawned more interest in the space elevator concept from the scientific and space advocacy community. For space exploration proponents, the single biggest challenge with the dreams and visions of exploring and colonizing other celestial bodies is the challenge of getting heavy payload systems away from the huge gravitational field the Earth presents. A technological leap in transporting such systems safely and cheaply into GEO would essentially open up the rest of the solar system for heavy robotic and follow-on human exploration and potential colonization. Suffice it say, the upside of such revolutionary systems is huge for exploration proponents.

In 2008, the International Space Elevator Consortium (ISEC) was formed to continue the advancement of the space elevator concept. The organization's mission is to (ISEC n.d.a.):

- Provide technical leadership promoting development, construction, and operation of space elevator infrastructures;
- Become the "go to" organization for all things space elevator;
- Energize and stimulate the public and the space community to support a space elevator for low-cost access to space; and
- Stimulate Science Technology Engineering & Math (STEM) activities while supporting educational gatherings, meetings, workshops, classes, and other similar events to carry out this mission.

Since 2008, the ISEC organization has taken the lead in the United States further developing the technical concepts of a space elevator. Their vision is (ISEC n.d.a.): "A world with inexpensive, safe, routine, and efficient access to space for the benefit of mankind."

Another major player in the space elevator community is the Japanese Space Elevator Association (JSEA). The Japanese have devised similar concepts to the space elevator, with technical enhancements to the current space elevator system architecture ISEC has proposed. Unfortunately, the JSEA website (www.jsea.jp) is not translated into English; the latest Japanese concept has been discussed by the ISEC community.

1. Current State of Space Elevator Research

After the NASA NIAC efforts and Edwards' book, the subsequent research on the SETS was published in 2013 through the International Academy of Astronautics (IAA) (Swan et al. 2013). This effort built upon the science and engineering of the NASA NIAC study, updating all major sections of the latest space elevator concept. A few major technical changes were also explored in the system architecture of the space elevator; the latest proposed system architecture will be discussed in the next section.

The ISEC group has completed multiple major collaborative research efforts since their inception. Other recent research on the space elevator concept that is not associated through the ISEC group is hard to find. It appears that all academia who have focused on the topic have recognized that the ISEC group is the best way to ensure research on the space elevator topic will be peer reviewed and will contribute to the community in the most efficient and organized manner.

ISEC has established a sound future research master plan with a rhythmic, consistent approach to studying the major technical challenges to the space elevator concept. The research drumbeat ISEC as stated on the ISCE website includes:

- Yearly Conference—ISEC has been organizing a conference intermittently since 2002, and yearly since 2008 in Seattle, as the prime opportunity for scientists, engineers, and researchers to come together and discuss the space elevator concept in an academic type setting.
- Year Long Studies—ISEC sponsors a focused annual research topic to ensure progress in a certain discipline. The list of these major efforts can

be found on the ISEC website, the latest focused research effort for 2017 is “Design Considerations for Space Elevator Simulation.”

- International Cooperation—ISEC supports many activities around the globe to ensure that space elevators keep progressing toward a developmental program.

- Competitions—ISEC has a history of actively supporting competitions that push technologies in the area of space elevators. The initial activities were centered on NASA’s Centennial Challenges called “Elevator: 2010.” Inside this were two specific challenges: Tether Challenge and Beam Power Challenge. The highlight was when Laser Motive won $900,000, in 2009, as they reached one kilometer in altitude racing other teams up a tether suspended from a helicopter.

- Publications—ISEC publishes a monthly e-Newsletter, yearly study reports, a technical journal (*CLIMB*) and a magazine (*Via Ad Astra*) to help spread information about space elevators (ISEC n.d.b.).

- Reference Material—A space elevator library, including a reference database of space elevator related papers and publications has been organized and constantly updated (National Space Society n.d.)

- Research Committee—The ISEC group’s research committee is responsible for setting the annual theme in which the yearlong study focuses on. The past focused studies go back to 2010 and include the following topics (ISEC n.d.c.):

  - 2017—Design Considerations for Space Elevator Simulation
  - 2016—Design Considerations for the Apex Anchor and the GEO Node
  - 2015—Design Characteristics of a Space Elevator Earth Port
  - 2014—Roadmaps and Architectures
  - 2013—Tether Climber
  - 2012—Operating and Maintaining a Space Elevator
  - 2011—Research and thought targeted toward the goal of a 30 MYuri tether
  - 2010—Space Debris Mitigation—Space Elevator Survivability (ISEC n.d.a.)

With all of the research material available on the space elevator concept, it is clear that there is a growing body of technical knowledge on the subject that appears to be well organized. Technical challenges and risk definitely exist and will be discussed in the next sections, but it is evident that a number of well-respected scientists and engineers are committed to developing and testing the technical systems associated with the space elevator to make it a technically feasible system possible of being developed within the first half of this century.

2. Most Recent Space Elevator System Architecture

Various space elevator system architectures have been developed throughout the years. The most robust proposals in terms of scientific engineering and conceptual studies include the following major subsystems, as stated in the Fitzgerald et al. (2015) paper on Space Elevator System Architectures:

1. Earth port/marine node
2. System tether also referred to as ribbon or cable
3. Tether climber(s)
4. GEO node
5. Interplanetary payload
6. Apex anchor (Fitzgerald et al. 2015)

In the past 20 years, three leading space elevator system architectures have evolved: the Edwards architecture, the IAA architecture, and the Obayashi architecture. Figure 4 shows this system architecture in image format, and Table 5 highlights the major characteristics of these three architectures.

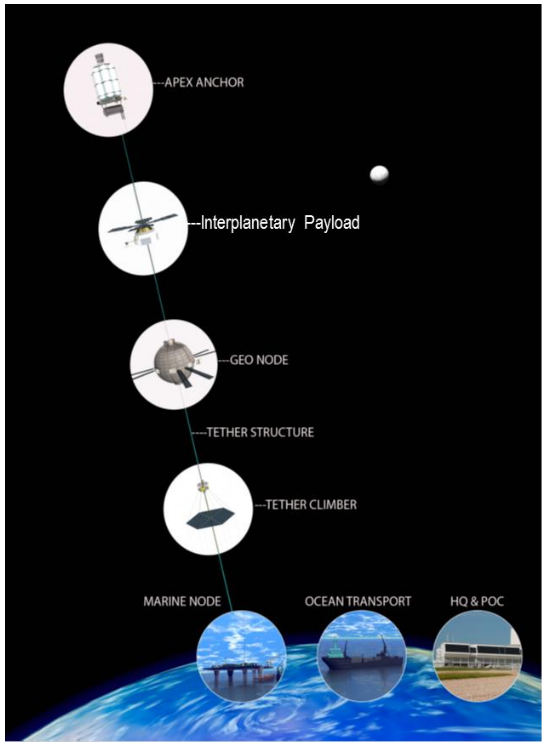


Figure 4. Space Elevator Architecture. Source: Fitzgerald et al. (2015).

Table 5. Three Main Space Elevator System Architectures.
Source: Swan and Swan (2016).

Major System Characteristics	**Dr. Edwards' Architecture (2002)**	**IAA Architecture (2013)**	**Obayashi Architecture (2013)**
Overall Space Elevator System Length (km)	100,000	100,000	96,000
Marine Node Characteristics	Ocean going oil platform	Ocean going oil platform or retired aircraft carrier	Port Extension from Island, 49 Million Metric Tons, 400 meter diameter
Ribbon Characteristics	Width—1 meter, curved	width—1 meter, curved	width—0.5 meter, curved, with 2 cables per carrier
Ribbon Design Characteristics	Woven with multiple strands	Woven with multiple strands	Many cables leading to massive tether climbers
Ribbon Material	Carbon nanotubes with 100 GigaPascals (GPa) strength at 1.3 grams/cm^3 density	Carbon nanotubes with 32–45 GPa strength at 1.3 grams/cm3 density	Carbon Nanotubes with 150 GPa capability
Loading Capability	Seven concurrent climbers on the ribbon	seven concurrent payloads on the ribbon	Six concurrent payloads on the ribbon (both up and down)
Power Source	Terrestrial Lasers	Solar power after 1st 40 kilometers	Laser power from ground or space
Cargo Capability	14 metric tons (tether climber 6 MT)	14 metric tons (tether climber 6 MT)	79 MT payload, climber 100 MT
Human Rated	No	No	Yes
Architecture Strategy	N/A	Baseline is one replicating space elevator (used to produce all others) and then pairs sold to operating companies. Initial concept, 3 pairs around the world.	One large space elevator with maximum capability.
Construction Strategy	The first space elevator will be built from GEO; then, once the gravity well has been overcome, it will be replicated from the ground up.	The first space elevator will be built from GEO; then, once the gravity well has been overcome, it will be replicated from the ground up.	The first space elevator will be built from GEO; then, once the gravity well has been overcome, it will be replicated from the ground up. First cable in 17 years, then a large capability after 18 years of building up the cable.
Projected Operational Date	~10 years after construction start date after mature materials	2035 operational start date	2055 Operations
Overall Estimated Construction Cost	$6 billion USD	$13 billion USD for first pair, after replicator space elevator	$100 billion USD
Estimated Cost per kg to Geo:	$150 USD	$500 USD	$50–100 USD

The main differences in the first two architectures (Edwards and IAA system) are in the powering of the tether climbers, the required estimated strength of tether material, the cargo capability, the overall projected cost to construct, and the estimated cost per kg to GEO. The reason for these differences is the IAA architecture, which is mainly built upon the technical analysis of the Edwards architecture, with additional updates from research completed after the Edwards architecture was proposed.

The Obayashi architecture is quite different from the IAA and Edwards architecture in that this design incorporated a human transport requirement into the overall design of the space elevator. The previous architectures did not propose human transport via the space elevator, only cargo, to minimize the size, strength, and complexity of the tether and tether climbers. This is evident in the much larger numbers required for the Obayashi architecture for the strength of the tether, the total cargo capacity, total cost, and longer projected operational date. The Obayashi architecture also differed in the following characteristics:

- Proposed Earth port on an island at or near the equator (as opposed to an ocean man-made structure);
- Number of tethers and tether characteristics;
- Strength of tether (150 GPA versus 25–35 MYuri);
- Cargo capacity (79 metric tons versus 14–20 metric tons);
- Operational date (2055 versus 2035);
- Total cost ($100b USD vs $13b USD); and
- Estimated cost per kg ($50–100 USD vs $150–$500 USD)

The fact that there are multiple architectures being proposed at this early stage of system development is ultimately a good thing and should help to develop the best system to put forward. Also, the chances of the system actually being built increases with multiple "players" around the world vying to be the first to construct such a massive, globally disruptive system.

D. CHAPTER SUMMARY

This chapter focused on providing the technical, operational, and developmental details of the two system alternatives. First, the details of the recent new major entrants into the rocket-based transportation alternative were presented. Then, a short discussion on non-rocket based transportation alternatives was presented, followed by a detailed presentation on the leading non-rocket based alternative, the space elevator, was presented. Now that the two system alternatives have been thoroughly described, the next chapter will tie the MOPs developed in Chapter II and use them to compare these two system alternatives.

IV. COMPARATIVE ANALYSIS OF ROCKETS TO THE SPACE ELEVATOR

The previous chapter presented the technical, operational, and developmental details of both rocket and non-rocket based systems. This chapter presents a comparative analysis between system alternatives. The MOPs developed in Chapter II will be used to compare the two system alternatives. Additional capability differences will be discussed.

A. FUTURE PROJECTED TECHNICAL CAPABILITIES OF SPACE ELEVATOR VERSUS ROCKETS: CARGO CAPACITY AND COST

The space elevator has some definite advantages and unique characteristics that make it enticing compared to existing rocket-based systems, assuming the major technical hurdles can be overcome. So how does a space elevator compare to projected near future rocket systems in terms of the two main MOPs identified earlier: payload capability and cost per kg to orbit? Table 6 is an update of Table 3, and here includes estimated space elevator capabilities. A comparison of both system alternatives payload capacity and cost to GEO yields some interesting points:

- Compared to all rocket systems currently operational (Ariane 64, SpaceX Falcon 9, and ULA Atlas V), the space elevator would yield much higher payload capacities by a factor of ~6, and much lower cost per kg to orbit by a factor of ~70.
- A comparison of the space elevator to near future projected heavy payload capacity rocket systems (NASA SLS and SpaceX ITS) is a much different story.
    - Comparing the space elevator to the SLS, the estimated payload capacities to orbit are about the same; however, the projected to orbit cost of the SLS is much higher than the space elevator, by a factor of 120.
    - Comparing the space elevator to the ITS, the estimated payload capacity of the ITS is higher than the space elevator by a factor of ~9, and the projected to orbit costs are roughly similar.
    - Both the NASA SLS effort and the SpaceX ITS rocket systems, if built to currently advertised capacities and costs to orbit, could compete with the payload capacity of the space elevator. The

> SpaceX ITS would beat the NASA SLS system significantly in terms of payload capacity and cost to orbit.

Figures 5 and 6 show graphically a comparison of the space elevator to near future rockets' payload capacity and cost to GEO.

Table 6. Space Elevator vs. Current/Near Future Rocket-based Systems Technical Capabilities. Source: Smith (2016); Berger (2017); SpaceX (n.d.b.); Musk (2017); Kyle (2017).

Capability	SPACE ELEVATOR (a)	Ariane 64 (b)	Blue Origin BE-4 (c)	SpaceX-Falcon 9 (d)	SpaceX -Falcon Heavy (d)	SpaceX-ITS (e)	NASA–SLS Block 1A (f)	ULA Atlas V (b)
Payload Capacity to GEO (unless otherwise noted, MT)	14–79	10	13	8.3	26.7	300[i]	19.5–50 tons[iii]	8.9 tons[iii]
Estimated Cost to GEO ($ USD/KG, see notes below)	$50–500	$13,891–$16,979	No Data	$11,272.73	$11,250	$140[ii]	$20,000–40,000	$27,867.41
Projected Operational Date (year)	2035–2055	Currently operational	2019	Currently operational	2018	2023	2023	Currently operational
Planned Reusability	fully reusable, with potential daily transports to GEO	None planned	plan: 1st stage, up to 100 times	Still testing capability	Still testing capability	see note [iv]	None planned	None planned

References: (a) (Smith 2016) (b) (Berger 2017) (c) (SpaceX n.d.b.) (d) (Musk 2017) (e) (Kyle 2017)
Notes:
(i) Fully reusable payload to LEO
(ii) Estimate E. Musk presented as cost per ticket for passenger to travel to Mars.
(iii) Reported in tons, not metric tons, 1 ton = 0.907 metric tons
(iv) Targeted reuse per vehicle: 1,000 uses per booster, 100 per tanker, 12 per ship.

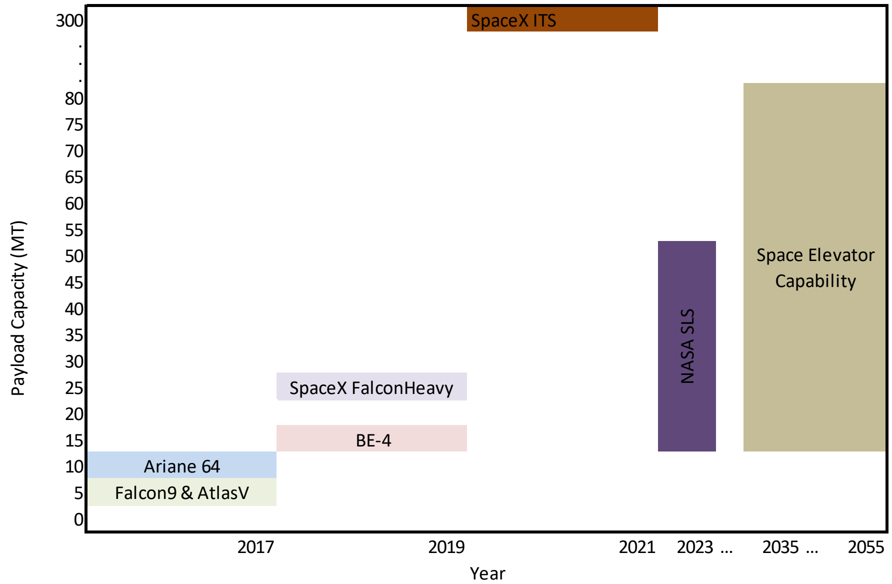


Figure 5. Payload Capacity (Range) vs. Year System Operational.

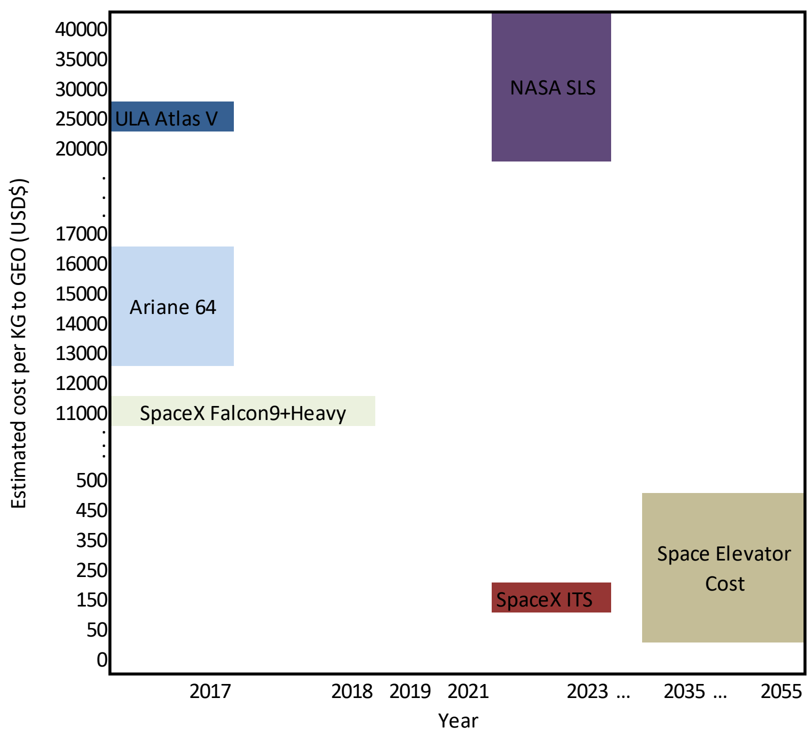


Figure 6. Estimated Cost per kg (Range) vs. Year System Operational.

B. HEAVY MISSION PAYLOAD CAPABILITY COMPARATIVE ANALYSIS

A common tool in the systems engineer's toolbox is to perform scenario use-case analyses to compare various system designs in performing a mission. Such an analysis was performed to compare rocket-based transportations systems capability to space elevator. Four different missions were selected. One mission had two variants so there were a total of five different scenarios used to compare the MOPs between the space elevator and rocket systems. These missions are:

- International Space Station (ISS) Total Mass lifted to LEO;
- Typical re-supply missions to ISS;
- Lockheed Martin Mars Base Camp mission (Cichan et al. 2017); and
- Two variations of a Space Based Solar Power Mission, a lower and upper total mass estimate of the mission (Mankins 2012).

These missions were chosen through a literature search on previous and future heavy lift missions. The ISS initial build up and re-supply missions are the only two missions that have occurred and have historical data on the total tonnage actually lifted into the orbit. The Lockheed Martin Mars Base camp mission and the spaced based solar power missions were selected due to the amount of literature and total payload capacity required data being available. The Lockheed Martin Mars mission and the space based solar power mission are very heavy lift type missions in terms of the total tonnage of system material that would need to be lifted into orbit. Additionally, these last two missions would benefit from in-space construction, which is a unique capability the space elevator would offer.

A simplified number of missions and mission total transportation costs were calculated by dividing the total payload capacity required for each mission by the payload capacities and cost per kg MOP capabilities for the space elevator and the top three (in terms of payload capacity) future rocket systems: the SpaceX falcon heavy, SpaceX ITS, and the NASA SLS rockets. Table 7 compares the number of lifts/launches and the estimated total cost to lift the five different space missions' total tonnage for each of the transportation systems. Figures 7 and 8 compare the differences for each transportation system to accomplish all of the missions, illustrating the number of lifts/launches and total cost required to complete the missions.

What becomes clear in this scenario analysis is the major leap the SpaceX ITS would present in both payload capacity and cost to orbit. The space elevator competes well with all other systems in development, except for the ITS. As mentioned earlier, SpaceX has made some bold claims with its ITS; whether these claims can become reality still remains to be seen. Other observations from this use case analysis include:

- The SpaceX ITS is the clear winner in terms of minimal missions and lowest cost
- The space elevator is the next best system
- The SLS would require fewer launches but cost more compared to the Falcon Heavy rocket

One note to make on the ISS use case analysis, since the ISS is located in LEO, the physics behind having a launch gate from the Space Elevator to LEO is challenging. This is such a difficult challenge, such that the latest space elevator system architectures do not even propose having a LEO launch gate, since enough delta-V would not be available in LEO. The suggestion that a space elevator could lift the ISS or other systems to LEO is included for comparative purposes only. One solution would be to launch systems into higher orbits and then allow them to achieve LEO; however, this analysis was beyond the scope of this effort.

Results of this use case analysis indicate that near future rocket-based systems can achieve similar results in the main MOPs payload capacity and cost when compared to the space elevator. The next section will now focus on a comparison of the two system alternatives using the other MOPs identified in Chapter II.

Table 7. Use Case Analysis Rockets vs. Space Elevator. Adapted from Melina (2017); Cichan et al. (2017); Mankins (2012).

Mission Use Case Information	MT	Space Elevator		SPACE-X Falcon Heavy		NASA SLS		SpaceX ITS	
		# of lift missions	**Total Cost ($M)**	**# of launches**	**Total Cost ($M)**	**# of launches**	**Total Cost ($M)**	**# of launches**	**Total Cost ($M)**
International Space Station Total Mass (Melina 2017)	419.6	9	$209,800	16	$4,720,500	14	$12,588,000	2	$58,744
International Space Station Maintenance Mass (annual) (Melina 2017)	28	1	$14,000	2	$315,000	1	$840,000	1	$3,920
Lockheed Martin Mars Base Camp Program (Cichan et al. 2017)	423.85	9	$211,925	16	$4,768,313	14	$12,715,500	2	$59,339
Space Based Solar Power System Mass (1 system, lower est, (Mankins 2012))	3,000	60	$1,500,000	113	$33,750,000	96	$90,000,000	10	$420,000
Space Based Solar Power System Mass (1 system, upper est (Mankins 2012))	25,000	500	$12,500,000	937	$281,250,000	794	$750,000,000	84	$3,500,000
	TOTALS	579	$14,435,725	1084	$324,803,813	919	$866,143,500	99	$4,042,003

Key Parameters (from previous table)	MT to GEO	Cost per KG to GEO	Cost per MT to GEO
SETS Ton lift capacity per tether climber	50	$500	$500,000
SPACEX Falcon Heavy	26.7	$11,250	$11,250,000
NASA SLS	31.52	$30,000	$30,000,000
SpaceX ITS	300	$140	$140,000

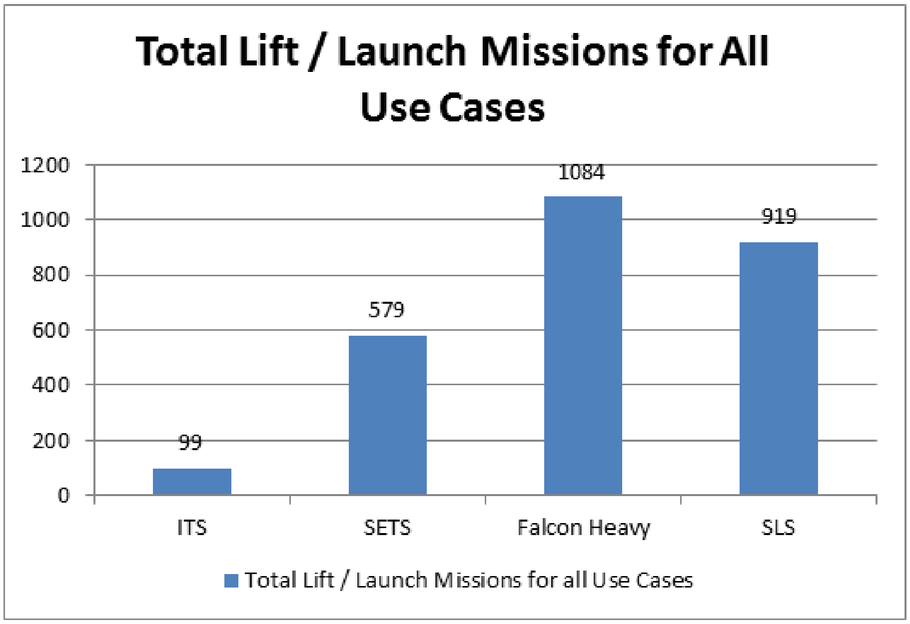


Figure 7. Total Number of Lift or Launches for All Missions.

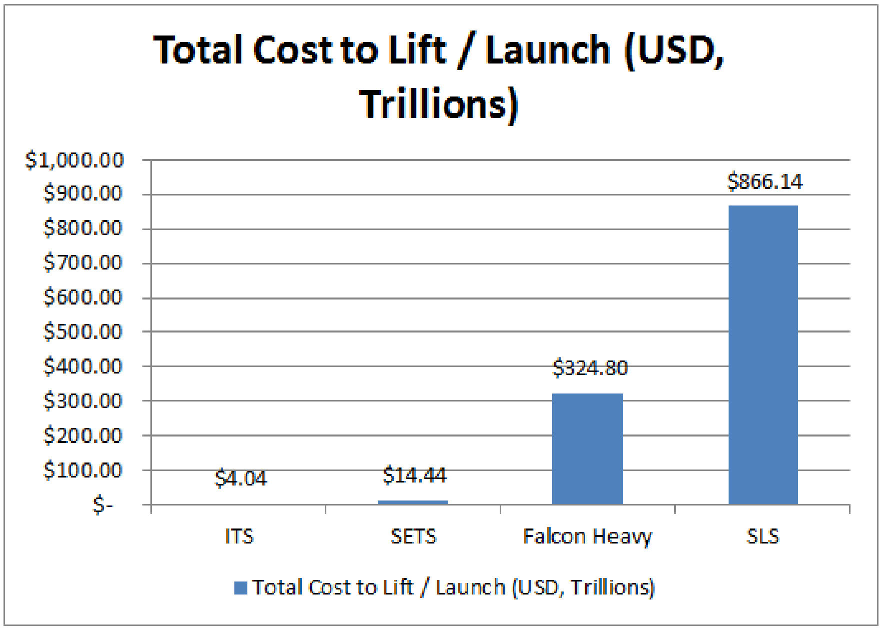


Figure 8. Total Cost to Lift or Launch for All Missions.

C. FUTURE PROJECTED TECHNICAL CAPABILITIES OF SPACE ELEVATOR VERSUS ROCKETS: ALL OTHER MEASURES OF PERFORMANCE

As discussed in the previous section, the main MOPs cargo capacity and cost to orbit were analyzed between the two systems. Now, the additional MOPs developed in Chapter II are discussed and a comparison of the two system alternatives is performed for each MOP.

1. Historical safety record/safe transport through atmosphere: **No comparison yet**
2. Rockets: The historical safety record of rockets is quite good, when comparing the historical number of successful launches to launches where a safety issue has occurred
3. Space elevator: The Space elevator has no safety record yet to compare.
4. Launch flexibility, geographic location: **Advantage rockets**
5. Rockets: There are limited number of launch sites around the world, currently operated by only a handful of countries
6. Space elevator: Launch location is limited to the equator
7. Launch flexibility, weather impacts: **Advantage space elevator**
8. Rockets: Weather impacts launch dates on many instances
9. Space elevator: Space elevator lifts would be less impacted by weather events;
10. Initial operating capability: **Advantage rockets**
11. Rockets: Near future rockets with comparable payload capacity are planned to be operational by the mid-2020s
12. Space elevator: The earliest planned operational estimate for the space elevator is 2035
13. Unique differences of system capabilities: **Advantage space elevator**
14. Rockets: limited in capability to capture and return systems to earth and to offer major in-orbit construction
15. Space elevator: could offer the unique capability to be able to transport systems back from space to the earth. Another unique capability space elevator could offer is the ability to facilitate work on systems in space,

which could occur at one of the space gates. Systems could begin to be designed in a completely different way to take advantage of this fact.

16. Geopolitics of system alternatives: **Advantage rockets**

17. Rockets: The geopolitics associated with rockets is more based on market based international company business geopolitics

18. Space elevator: The major construction of a space elevator on the planet would face serious geopolitical challenges. These challenges are further discussed below.

A comparison of the two systems based on the other MOPs indicates that both systems have unique capabilities and characteristics. The near future rockets system alternative is deemed to be the better system in three of five MOPs with there being no comparison (yet) for the first MOP, safety. Both systems have unique characteristics and capabilities and depending on the requirements of a mission, one system could be preferred over the other. Summarizing the last two sections MOP comparison, indicates that if a rocket with projected capabilities, such as the SpaceX can be built, then near rocket-based systems have a competitive advantage and are superior over the space elevator system in five of the seven MOPs identified in Chapter II. The next section will discuss the technical hurdles and risks associated with both system alternatives.

D. TECHNICAL HURDLES AND RISKS

There are many unknowns when comparing future rocket systems to the space elevator concept. The author is careful not to make any major claims as there are still some major obstacles to overcome for both systems. The rocket-based systems have the proven track record and appear to be on an upward evolutionary trajectory in many of the MOPs used to compare the two systems. However, the technical drawbacks of rocket systems mentioned earlier will not go away with the foreseeable advancements, which is why the space elevator system alternative continues to remain a potential alternative orbital transportation system.

Some of the major risks associated with both system alternatives are:

- Will the SLS and/or the ITS be able to deliver on payload capacity and current schedule to launch operationally?

- Will the ITS be able to achieve the cost to orbit that SpaceX claims?
- How well will the "reusability" of the rocket-based systems continue to progress?
- Can "free-market" approach continue to drive down rocket-based cost to GEO?
- Can the space elevator overcome the technical challenges associated with its ultimate construction?

Now technical hurdles and risks will be discussed for each system alternative.

1. Technical Hurdles and Risks Associated with Rocket-based Transportation Systems

As rocket systems continue to advance and grow larger, to accommodate larger mission payloads, they are still tied by the fundamental rocket equation, pioneered by Konstantin Tsiolkovsky in 1903 (Pettit 2012). The limiting factor of any rocket-based system is tied to this basic equation, which is tied to Newton's second law of conservation of motion. The rocket-based system uses massive amounts of fuel to propel itself, payload and fuel into orbit. A typical percent both theoretically derived and seen in practice is 85–90% of the weight of a rocket is the fuel required to escape the Earth's gravitational pull.

Understanding that if one makes a rocket bigger will not make it more efficient and could make it less efficient in terms of percent payload capacity, depending on how it is designed. This physical limitation continues to inspire the scientific community to look for "a better way" to leave the huge gravitational pull of the Earth.

Other technical drawbacks to rocket-based systems include:

- Potential environmental hazards of rocket fuel on the upper atmospheric ozone layer;
- The vibrational and g-forces that the rocket's payload is subjected to when escaping the Earth's gravity (i.e., it is an extremely bumpy ride);
- The infrequent and potentially continual delays of launches due to weather and a number of other technical issues; and

- The limited number of launchpad locations and limited amount of launch logistic infrastructure.

When a systems engineer is comparing various system architectures to fulfill stakeholder requirements, these drawbacks of rocket-based systems should be considered. Indeed, as will be discussed later, these drawbacks for rocket-based systems are some of the main points of motivation scientists and engineers mention when continuing to work for alternative OTSs.

2. Technical Hurdles and Risks Associated with Space Elevator

Major technical hurdles exist before a space elevator can be developed, constructed, and operational. The research done leading up to the 2013 IAA book (Swan et al. 2013) has done an excellent job of identifying and categorizing the existing technical hurdles. These technical hurdles are summarized in Table 8 and Figure 9. The highlighted sections in Table 8 indicate the sub-systems of the space elevator with lowest TRL and highest risk associated with getting to technical and operational development. The obvious "weakest link in the chain" is the strength of materials in developing the tether. The tether climber also has a low TRL/high T risk sub-system. Continued recent advancements in the CNT material continue to give hope to the space elevator and space community at large. Additional incremental advancements on all sub-systems must continue for the space elevator vision to become reality. The two highest risks to the tether are space debris and strength of materials. These are discussed below.

Table 8. Space Elevator Technical Risks and Hurdles. Adapted from Swan et al. (2013).

Space Elevator Major Subsystem Component	**Similar system's availability**	**Expected Year to Maturity**	**Current TRL Level**	**TRL Level by 2030**	**Remarks**
Tether	Material exists but not strong enough, and not designed for space environment	2035+	2	7	Strength required for space elevator in the long lengths in hostile environment. This technology will need significant testing. Estimates will vary with knowledge of material and progress in strength to weight ratio. Major development funding required. Terrestrial version will be available by 2030 in greater than 1,000 km lengths.
Apex Anchor	Satellites exist	2020	5	8	Reel-out and control of tether must be tested in-orbit Reel-out in vacuum of long material will require design and testing of components in orbit.
GEO Node	exists	today	6	9	Routine to develop
Tether Climber	exists	2020	4	8	Large lightweight solar panels will require development. Major design effort needed for system of climber; however, not beyond the knowledge of current satellite designers. Should be tested in orbit.
Marine Node	exists	2015	8	9	This will be a routine development except for the tether terminus. Developers should leverage deep-ocean drilling platforms. Deep ocean drilling platforms and sea launch platform can be models.
Ocean Going Cargo Vessel	exists	today	9	9	Routine
Helicopter Transport	Exists	today	9	9	Routine
Operations Center	Exists	today	9	9	Routine

Note: highlighted areas indicate the sub-systems with lowest TRL and highest risk associated with getting to technical and operational development.

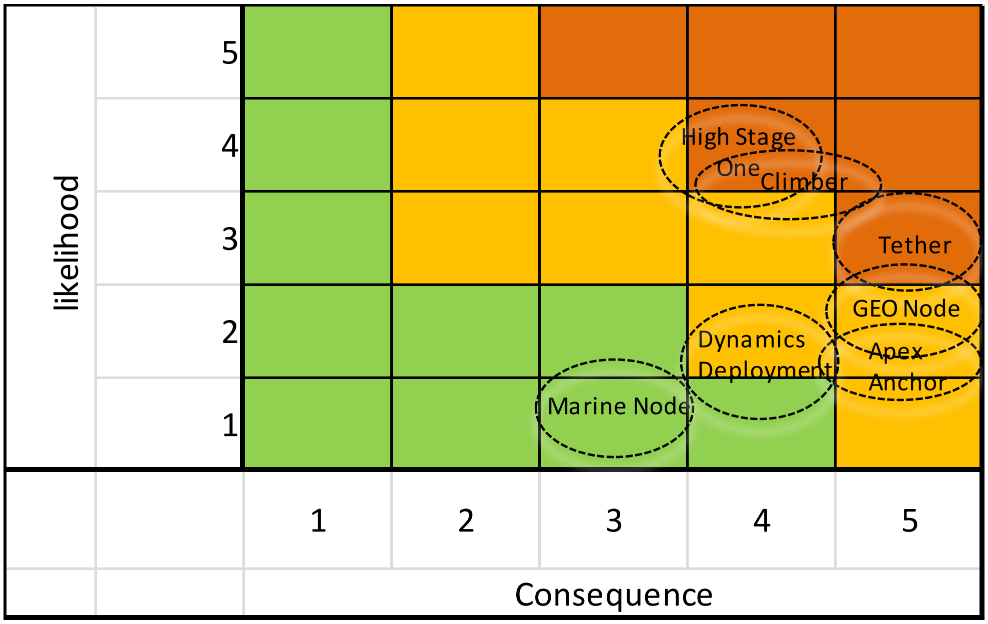


Figure 9. Space Elevator System Component Risk to Construction Matrix.
Source: Swan et al. (2013).

a. Space Debris

The space elevator would need to deal with the risk of space debris damaging or catastrophically destroying the space elevator tether. The latest space elevator studies conducted on this issue and indicate that the space elevator could conceivably be moved to avoid larger space debris, and smaller ones would not be able to damage the toughness of a CNT-based tether (Swan et al. 2013).

b. Strength of Materials Risk

As discussed above, the major technical challenge associated with a space elevator concept being feasible is discovering a new material that has an extremely high tensile strength to weight ratio (typically measured in GPa/g/cm^3, though the space elevator community has coined a new measurement term called MYuri, where 1 MYuri = 1 GPa/g/cm^3). Past feasibility studies have detailed the required strength to weight ratio needed to support the space elevator concept to be on the order of 20–150 GPa/(g/cm^3), depending on the system concept and system architecture (Swan et al. 2013). At one time, this strength of material requirement seemed impossible to meet; now, it seems possible through innovation in material science that continues to evolve. The types of materials that could provide the estimated strength to weight properties required to make a space elevator technically feasible are only possible today in the laboratory environment. The most promising of these materials are called carbon nanotubes (CNT). Carbon nanotubes are cylindrical carbon molecules with novel properties that include maximum tensile strength of more than 50 times that of steel wire, the ability to carry large currents with little heating, and able to conduct electricity (Gay, Kaufman, and McGuigan 2005). Figure 10 compares CNTs with other common high-tensile strength materials (Haase 2017). Figure 10 clearly shows the revolutionary gain CNTs and other similar CNT like-materials (Boron Nitride NanoTubes, BNNT) could make in providing an extremely high tensile strength to weight, if the material can make its way out of the laboratory and into production.

The next question is if this material becomes an industrial grade material for use in such applications, when can the engineer/scientist expect to be able to utilize the revolutionary properties this material presents? Figure 11 shows a plot of various CNT materials and different manufacturing processes and the growth of the tensile strength vs time (Haase 2017). As Haase points out in his research on this subject, there is a general upwards trend in the continued progress of CNT process breakthroughs yielding higher and higher tensile strengths. According to Haase, if this trend continues, he expects a material that could support a space elevator concept by the mid-2030s.

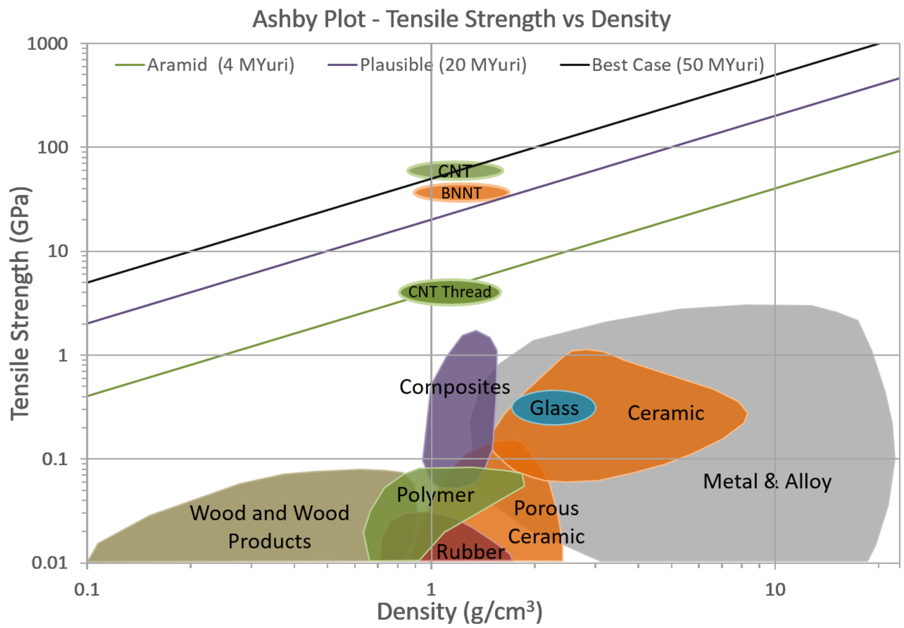


Figure 10. Ashby Plot of Tensile Strength versus Density of Various Materials. Source: Haase (2017).

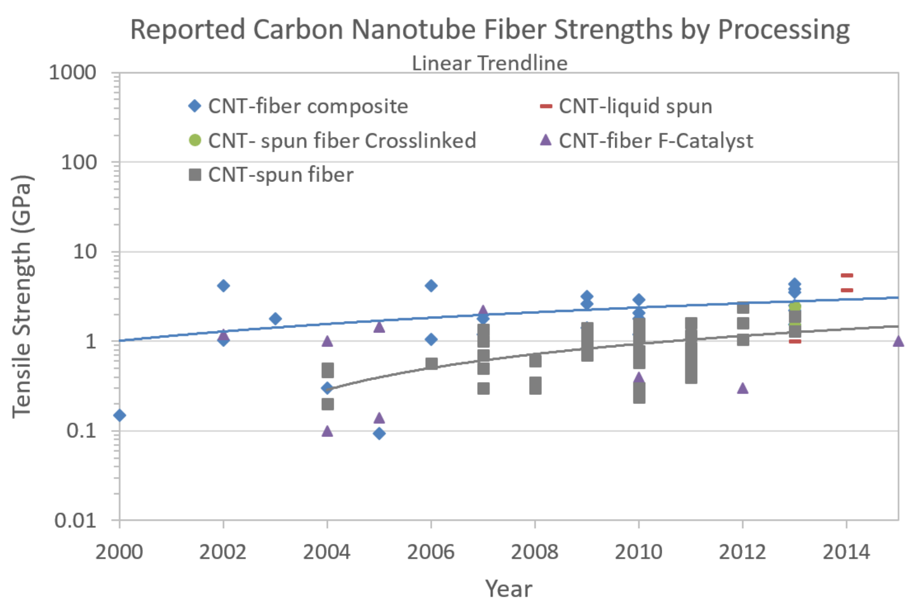


Figure 11. Tensile Strength vs. Time of CNT Materials. Source: Haase (2017).

In summary, quite a few technical challenges are related to the space elevator, but, assuming the continued growth in tensile strength of materials, none appear to be so challenging to stop the concept development. The space elevator community continues development of the major subsystem components of the space elevator.

E. CHAPTER SUMMARY

This chapter utilized the MOPs developed in Chapter II to compare and contrast the two system alternatives. A use-case analysis was utilized to further compare and contrast both systems capabilities in terms of payload capacity and cost and strengthened. The results of the comparison indicated near future rockets have the advantage because they are currently in existence and near future rocket systems will be able to carry similar payload capacity at comparable cost, if the projected capabilities of the SpaceX ITS rocket are realized. This chapter then discussed some of the unique characteristics of both systems as identified in the other MOPs in Chapter II. Near future rocket-based systems had the competitive advantage over the space elevator system in three of the five MOPs. Putting both MOP discussions together, indicate that rocket-based systems have the competitive advantage of the space elevator system in five of the seven MOPs identified. However, both systems have unique characteristics and capabilities and depending on the requirements of a mission, one system could be preferred over the other.

Finally, a discussion on the technical hurdles and risks associated with both systems was discussed. While the major technical hurdles for the space elevators are very challenging, they are not insurmountable. The space elevator community has elegantly laid the path forward to continue to make technical strides and reach technical objectives for each sub-system, such that the entire system could be technically realized by the mid-2030s. Whereas the major challenges associated with rockets reaching similar capabilities as the space elevator are already being accomplished. The next chapter will discuss the technical and geopolitical impacts of advances in payload capacity and reduction in cost per kg to orbit.

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V. TECHNICAL AND GEOPOLITICAL IMPLICATIONS OF ADVANCES IN ORBITAL TRANSPORTATION SYSTEMS

This chapter focuses on both technical and geopolitical implications and impacts of increases in payload capacity and decreases in cost that either near future rocket-based transportation systems or a space elevator system could provide.

A. TECHNICAL IMPLICATIONS

An increase in payload capacity and cost reduction to orbit will impact the way the space industry designs space systems in the near future. Engineers will capitalize on the larger payload capacity and lower cost to orbit of near future rockets. As a representative example of these impacts, the added benefits to the Satellite Communications (SATCOM) industry will be further discussed in this section. A space elevator system would be potentially unrestricted by the aerodynamic requirements of leaving Earth's gravitational pull and achieving escape velocity. It would not have the extreme acceleration, shock, and vibration associated with a traditional rocket launch profile. Considering the capabilities of space elevator or larger payload reusable rockets, SATCOM engineers will be able to design satellite structures to support the systems necessary to meet mission requirements, rather than optimize and adapt satellite systems to fit a structure that is compatible with the size of a launch vehicle and the rigors of a launch sequence.

Constrained by structure and power available, the average satellite antenna system is typically limited to as few as one antenna configured for multiple frequencies, and optimized to communicate with multiple ground stations. Maximum gain in one frequency may lead to unsuitably low gain on another frequency, forcing a compromise in signal quality. Larger satellites, delivered by a large payload capacity rocket or space elevator, would provide increased physical structure to mount a greater number of antennas, providing maximum gain for numerous individual frequencies or narrower frequency bands. Additionally, large aperture optical and radar systems would benefit greatly from increased payload capacity.

Larger satellite vehicle structures also provide space for larger power generation, power storage, and power management systems, to include power amplifiers. In addition to providing the energy required to manage multiple antenna systems, the increased power capacity of a space elevator and/or advanced rocket delivered satellite provides the capability to generate signals well above the 10 to 100 Watt range typical of a traditional satellite that is limited by mass and available power. The increased power of the satellite will provide increased flexibility for uplink and downlink signals, facilitating effective communication for potentially disadvantaged ground stations with low power signals, small antennas, or both.

Capitalizing on the array of antennas and available power, and similar to the Advanced Extra High Frequency (AEHF) payload on the Military Strategic and Tactical Relay (MILSTAR), space elevator and/or advanced rocket delivered satellites could incorporate advanced on-board digital processing hardware, firmware, and software. This would facilitate on-orbit processing, ensure secure, high-speed communications, and provide flexibility in communication systems via on-orbit network management. The capability and autonomy of these advanced satellites will prove vital to the DoD, other government interests, and private entities, transmitting information in support of national security and economic interest.

The low cost per kg and increased payload capacity to orbit promised by space elevator and/or advanced rockets will produce major change in numerous space-based industries. The SATCOM industry will benefit from the democratization of satellite communication as a space elevator and/or advanced rockets are developed to place large satellites in orbit, satellites with capability and capacity similar to ground stations.

Finally, larger payload capacities will allow systems that are currently stuck on the drawing board or in laboratory experiments, like space-based solar power, to begin to make sense economically and from a space construction standpoint. As shown in Table 7, the lower launch requirements of the SpaceX ITS, or the steady lift operations of a space elevator, would be a game-changing transportation service that could make these type of advanced technology concepts much more feasible. The same holds true for interplanetary missions like the Lockheed Martin Base Camp Program (also shown in

Table 7). These types of interplanetary ships could now be built or assembled in orbit. The bottom line is major advancements in cost per kg and payload capabilities will have huge technical and economic impacts on the various space industries currently in their infancies, as compared to what they will be 10–50 years from now and beyond. In summary, major advances in both a larger payload capacity and a reduction in cost per kg to orbit will allow for major advancements in the way engineers and scientists approach designing space systems. The next section will focus on geopolitical impacts of such advancements.

B. GEOPOLITICS FURTHERING COMMERCIALIZATION OF ROCKET-BASED SYSTEMS

This section highlights some of the politicking that has been in play since new “start-up” rocket companies have entered what has traditionally been a one-customer (large government entities) serviced by major government industrial commercial companies (i.e., Lockheed Martin, Boeing). In addition to the technical challenges described earlier, there are also geopolitical challenges in pushing the industry forward. Often, these non-technical challenges can be even harder to overcome than the technical challenges.

Blue Origin is the creator of one possible replacement rocket for the Russian built RD-180, which the United Launch Alliance (ULA), a joint venture between Lockheed Martin and Boeing, have used exclusively since the 1990s and most recently as the first stage of its Atlas V propulsion system. The accelerated commercial development of the BE-4, Blue Origin’s first attempt at a replacement for the Russian built RD-180, is expected to be flight worthy in 2018, one year ahead of the Congressional mandate to wean America off the Russian rocket for national security payloads (Blue Origin n.d.). The Congressional directive came about because of a short-lived court order that blocked the purchase of the Russian manufactured RD-180 during a lawsuit filed by SpaceX against the United States (U.S.) Air Force “block buy” contract with ULA. During this trial, Congress became aware of America’s reliance on a Russian produced rocket as the sole capability to get national security systems into space (Foust 2014); even though Lockheed Martin had a license and much of the technical information to manufacture the

RD-180 in the United States, the estimated $1 billion (over five years) price led industry and government to abandon that investment long ago (Foust 2014).

The 2014 lawsuit that SpaceX filed against the U.S. Air Force was to be able to compete on all “single core” Evolved Expendable Launch Vehicle (EELV) launches. During the trial, SpaceX made the argument that ULA’s purchase of the RD-180 from the company NPO Energomash was in violation of Russian sanctions (Executive Order [E.O.] 13,661). The judge established a temporary ban on commercial dealings with NPO Energomash while three government agencies were tasked to determine the validity of this argument. Those three agencies could neither confirm nor deny the claim, so the injunction was lifted with a caveat that no future payment shall contravene E.O. 13,661 (Foust 2014).

Congress, now concerned about a possible violation, stirred commercial competition by mandating the “development of a next generation liquid rocket engine that enables the effective, efficient, and expedient transition from the use of a non-allied space launch engine to a domestic alternative for national security space launches…be developed not later than 2019…be developed using free and open competition” (Levin and McKeown 2014).

C. GEOPOLITICAL IMPACTS OF A SPACE ELEVATOR

If constructed, a space elevator system would be one of the most audacious construction projects in the history of mankind, on par with the pyramids of Egypt. Such a major human endeavor will no doubt have major geopolitical challenges along with the already discussed technical challenges.

The main geopolitical challenges of the development of a space elevator directly relate to the physical location of the space elevator and the security dilemma inherent with an unfettered physical line of transportation and communication to space. To support the geostationary orbit of a space station atop the space elevator, the associated ground station must be located on, or very near, the equator (Laubscher 2004; Swan 2004). Equatorial circumference of Earth is 40,074 kilometers, with a linear landmass of approximately 8,545 kilometers. The vast majority of land mass passes through politically challenged developing nations, not necessarily aligned, politically or economically, with spacefaring nations (Google Earth n.d.). Brazil, an emerging space power, provides the best option for land-based space elevator (Harvey, Smid, and Pirard 2010). The remaining 50,446 kilometers of Equatorial Ocean provide ample unclaimed surface area. Study of climatology and human behavior suggests an area of the Pacific Ocean located approximately 200–800 kilometers west of Galapagos is suitable for sea-based space elevator (Laubscher 2004; Swan 2004).

Adapting principles of maritime strategy to space strategy, the space elevator represents an area where terrestrial and space vehicles will converge and interface, potentially becoming a choke point in the space lines of passage and communication (Klein 2006; Grove 1988). A potentially conflict scenario of controlling an evolutionary "gate" to space, points to an eventual arrangement of the conditions for conflict over protection and control of the space elevator choke point, and the access it provides. In order to maintain peace, four treaties provide the basis for the current international space regime, widely known by their common names: The Outer Space Treaty (OST), UN Resolution 34 and 68, and the Conventions on Liability and Registration, with four additional agreements that specifically address military affairs (Dolman 2006). While these treaties have succeeded in preserving peace for the better part of four decades, they are merely cooperative agreements among participating nations united in the common good of space exploration.

As one of the dominant powers in space, the U.S. National Military Strategy both outlines the importance of, and declares U.S. commitment to, preserving access to space and security of space (Dolman 2006; Joint Chiefs of Staff 2015). Given the current dominance of the U.S. as a space power, the idea of U.S. leadership in establishing, managing, and controlling a space elevator is rational. Applying the political realist model, *Realpolitik*, in conjunction with U.S. dominance in space, points to Everett Dolman's *Astropolitik* as valid model for U.S. controlled space access via a space elevator. U.S. *Astropolitik* includes three steps:

1. Withdraw from the current international space regime and establish free-market sovereignty in space;

2. Exploit current and near-term U.S. space superiority to construct and establish control of the space elevator choke point; and

3. Establish an agency to define, separate, and coordinate commercial, military, and civilian space and space access requirements (Dolman 2006).

The combination of U.S. space power capabilities coupled with American willingness to maintain control of an international system would establish a benign hegemony for the construction of the space elevator and control of space access (Dolman 2006). Unfortunately, as Mike Moore argues, an American attempt at unilateral space-dominance will alienate nations and people who might otherwise be allies and friends (Moore 2008).

The challenge for U.S. political and military leaders will be to preserve access and provide security, while preventing the appearance of hubris and upholding American exceptionalism (Moore 2008). The development of such a major evolutionary transportation system, such as the space elevator, would provide not only one of the greatest technical challenges (as described above) in the history of mankind, but also provide the greatest geopolitical challenge for control and protection of such a system.

The next chapter will summarize the conclusions and recommendations of this effort, as well as provide recommendations for further research.

VI. CONCLUSIONS, RECOMMENDATIONS, AND FURTHER RESEARCH

This final chapter of this thesis will summarize conclusions made during the research of this exciting topic, offer recommendations and areas for further research on topics that are important to consider when studying Orbital Transportation Systems (OTS).

A. CONCLUSIONS

Recent new entrants into the space rocket industry have forced innovations to happen faster than the traditional government and large corporation controlled industry has been accustomed to in the past. Additionally, a revitalized interest in the human population becoming a space-faring species, travelling to near future locations like the Moon and Mars, have helped focus more attention on getting larger human capable space systems into orbit. This revitalized focus has helped continue to increase payload capacities of rocket-based systems and continued to drive down the cost per kg to orbit. This in turn, makes the likelihood that humans will travel to and establish extra-planetary outposts and later on habitations more possible in this century.

This thesis has conducted a comparative analysis of near future, rocket-based capabilities with the space elevator transportation system. The results of this analysis are as follows:

1. Utilizing a systems engineering process, MOPs were developed to compare two OTS: near future rockets to a leading non-rocket OTS, the space elevator. Near future rockets have the competitive advantage over the space elevator in five of the seven MOPs identified. However, both systems have unique characteristics and capabilities and depending on the requirements of a mission, one system could be preferred over the other.

2. New major entrants into the rocket industry will continue to push an increase in payload capacity and decrease the cost per kg to orbit of near future rockets systems. The increase in payload capacity and cost per kg to orbit will impact the way space systems engineers and scientists design their systems in the future, to take advantage of these improvements. The Satellite Communications (SATCOM) community will benefit in the following ways:

i) SATCOM engineers will design satellite structures to support the systems necessary to meet mission requirements, rather than optimize and adapt satellite systems to fit a structure compatible with the size of a launch vehicle and the rigors of a launch sequence.
ii) Larger satellites, delivered by a large payload capacity rocket or space elevator, would provide increased physical structure to mount a greater number of antennas, providing maximum gain for numerous individual frequencies or narrower frequency bands. Additionally, large aperture optical and radar systems would benefit greatly from increased payload capacity.
iii) Larger satellite vehicle structures also provide space for larger power generation, power storage, and power management systems, to include power amplifiers. This increased power capacity would provide the capability to generate signals well above the 10 to 100 Watt range typical of a traditional satellite that is limited by mass and available power. The increased power of the satellite will provide increased flexibility for uplink and downlink signals, facilitating effective communication for potentially disadvantaged ground stations with low power signals, small antennas, or both.
iv) Capitalizing on the array of antennas and available power, and similar to the Advanced Extra High Frequency (AEHF) payload on the Military Strategic and Tactical Relay (MILSTAR), these new satellites could incorporate advanced on-board digital processing hardware, firmware, and software, to facilitate on-orbit processing, ensure secure, high-speed communications, and provide flexibility in communication systems via on-orbit network management.
v) The SATCOM industry would benefit from the democratization of satellite communication, satellites with capability and capacity similar to ground stations.
vi) Larger payload capacities will allow systems that are currently stuck on the drawing board or in laboratory experiments, like space-based solar power, to begin to make sense economically and from a space construction standpoint.
vii) Interplanetary ships could now be conceived to be built or assembled in orbit, with higher payload capabilities and lower costs per kg to orbit.

3. The space elevator, a non-rocket OTS alternative, appears to be technically feasible, with the assumption that tensile strength in materials, such as carbon nanotubes (CNTs) continued development.

4. Technical advantages of non-rocket OTSs like the space elevator make it quite an appealing system to continue to develop. It has advantages, such as:

i) A comparison of payload capacity "throughput" to orbit would indicate a space elevator system would be able to transport more payload to orbit then traditional rockets, unless significantly more launch infrastructure was developed. Most recent estimates on a single space elevator system indicate a tether climber could reach GEO on a daily basis, which would far outweigh rocket systems total annual throughput.

ii) A space elevator would offer the unique capability to be able to transport systems back from space to the earth. This characteristic was one of the benefits of the space shuttle, that a space elevator could reintroduce to the space community;

iii) The unique capability space elevator could offer is the ability to work on systems in space, at one of the space gates. Systems would begin to be designed in a completely different way, to take advantage of this fact.

5. Geopolitical challenges are being overcome in the USA to allow major new entrants into the rocket industry, which will continue to drive up rocket capability and drive down costs per kg to orbit.

6. Geopolitical challenges with developing a space elevator system will be quite daunting, as the major challenge will come with locating the Earth port of the system and facing the challenges associated with operating and protecting an evolutionary gateway to space.

The future for rocket-based systems looks very bright for the near term as multiple new-entrants continue to develop larger payload capacity rockets and continue to "compete" for (mainly SATCOM) business, thus driving down the cost per kg to orbit. This could have an adverse effect on continuing to develop alternate OTS, such as the space elevator, as R&D capitol that could be available for those systems gets swallowed up by new missions that can be accomplished now w/ the larger payload/lower cost. However, from a physics perspective, the rocket-based system is tied to the limitations of the rocket-Equation; one cannot simply ignore the rules and laws of Newtonian Physics. This disadvantage of rockets, plus the potential major advantages of having a consistent, daily to-orbit, very large payload capacity, at extremely cheap costs, makes the space elevator system (and other alternatives to rockets) worth the R&D dollars needed to invest in such alternative OTS systems.

B. RECOMMENDATIONS AND FURTHER RESEARCH

1. Recommendations

As part of the research and analysis into this topic, the following recommendations are made:

1. The author recommends that the space community and major funded players within the community (i.e., government and large corporations) continue to fund R&D efforts for the space elevator and other non-rocket OTSs. The potential upside these alternatives have warrants the effort to figure out how to make them technically and geopolitically feasible.

2. Similarly, R&D dollars should continue to be used for the development of CNTs and other new higher strength materials. The obvious benefit will not only be reaped from the space industry, but impact many areas in industry. It is hard to think of an industry that will not benefit from stronger and lighter material properties.

3. An obvious recommendation to make, but not so easy implement, is to continue pushing the envelope of space exploration and space activities. Currently, for technical people, it is still very difficult to find a job and a career in the space industry, compared to the other major applied science industries. This makes it hard for the best and brightest minds to continue to help to push advancements in the space industry. However, as the late great President Kennedy once said:

> We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone. (Kennedy 1962)

The future generations' continual push to reach beyond the previous generations by going back to Moon, Mars, and beyond, aided by considerable private capital investments from today's greatest entrepreneurs, will only continue the growth of the space industry and continued advancement of space systems further out into the solar system.

2. Further Research

1. The author recommends continued research in other non-rocket OTSs as briefly discussed in Chapter IV. Continuing advancements in so many different technical fields could also advance one of these other non-rocket OTS concepts.

2. The author recommends further research in the environmental drawbacks in rockets. When studying this topic, it did not appear that there has been a great deal of research on this topic. Similar to the ozone hole issue created by the use of chlorofluorocarbon (CFCs), before the 1970s ban, the potential adverse consequences of large-scale rocket operations make it an extremely important topic of research.

3. Further research is warranted to determine how and where the U.S. government, the DoD, and other large corporations can spend their R&D dollars wisely to ensure maximum return on investments. One avenue that seems to work very well, especially in the space industry, is in the form of a competitions or prizes.

This subject has been quite rewarding to study, and the future of space exploration will continue to draw enthusiasm from people from all corners of the Earth. The concept of being able to board a rocket ship or a space elevator and travel to another planet where a whole new human civilization is beginning is just too enticing, especially from an engineer's standpoint, not to want to be a part of the excitement, and participate in any way possible to contribute to this fascinating future.

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APPENDIX A. INCOSE TECHNICAL PROCESSES

Table 9 highlights the major technical processes identified in the *INCOSE SE Handbook*.

Table 9. Technical Processes. Adapted from INCOSE (2015).

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
4.1	Business or Mission Analysis Process		Defines the business or mission problem or opportunity, characterizes the solution space, and determines the potential solution class(es) that could address a problem or take advantage of an opportunity.
	Nominate Major Stakeholders	4.1.2.1	Although the detailed identification of stakeholders is undertaken in the “stakeholder needs and requirements definition process:, during business and mission analysis, the business managers are responsible for nominating major stakeholders and for establishing a stakeholder board.
	Define the Problem or Opportunity Space	4.1.1.4.b	* Review identified gaps in the organization strategy with respect to desire organization goals or objectives. * Analyze the gaps across the trade space. * Describe the problems or opportunities underlying the gaps. * Obtain agreement on the problem or opportunity descriptions.
	Characterize the Solution Space	4.1.1.4.c	* Nominate major stakeholders. * Define preliminary ConOps (describing the Concept of Operation for how a system works) from the operator’s perspective. * Define other preliminary life cycle concepts. * Establish a comprehensive set of alternative solution classes.
4.2	Stakeholder Needs and Requirements Definition Process		Define the stakeholder requirements for a system that can provide the capabilities needed by users and other stakeholders in a defined environment.

INCOSE 2015 SE Handbook Section Number/Name	Sub-Section	Definitions
Prepare for stakeholder needs and requirements definition	4.2.1.4.a	* Determine the stakeholders or ***classes of stakeholders*** who will participate with systems engineering to develop and define the stakeholder needs and translate these into system requirements phased throughout the entire life cycle. Capture these results in the ConOps. * Determine the need for and requirements of any enabling systems, products, or services.
Define stakeholder needs	4.2.1.4.b	* Elicit stakeholder needs from the identified stakeholders. * Prioritize the stakeholder needs to identify which to focus on. * Specify the stakeholder needs.
Develop the operational concept and other life cycle concepts	4.2.1.4.c	* Identify the expected set of operational scenarios and associated capabilities, behaviors, and responses of the system or solution and environments across the life cycle (in acquisition, deployment, operations, support, and retirement). * Define the interactions of the system or solution with the users and the operating, support and enabling environments.
Transform stakeholder needs into stakeholder requirements	4.2.1.4.d	* Identify constraints on the solution (imposed by agreements or interfaces with legacy or interoperating systems). * Specify health, safety, security, environment, assurance, and or other stakeholder requirements and functions that relate to critical qualities. * Specify stakeholder requirements, consistent with scenarios, interactions, constraints, and critical qualities.
Analyze stakeholder requirements	4.2.1.4.e	* Define validation criteria for stakeholder requirements. ** Includes Measures of Effectiveness (MOEs) and Measures of Suitability (MOSs), which are the "operational" measures of success that are closely related to the achievement of the mission or operational objective being evaluated, in the intended operational environment under a specified set of conditions (i.e., how well the solution achieves the intended purpose). ** These measures reflect overall customer/user satisfaction (e.g., performance, safety reliability, availability, maintainability, and workload requirements.) * Analyze the set of requirements for clarity, completeness, and consistency. Include review of the analyzed requirements to the applicable stakeholders to ensure the requirements reflect their needs and expectations.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Manage the stakeholder needs and requirements definition	4.2.1.4.f	* Negotiate modifications to resolve unrealizable or impractical requirements. * Establish with stakeholders that their requirements are expressed correctly. * Record stakeholder requirements in a form suitable for maintenance throughout the system life cycle. * Establish and maintain through the life cycle a traceability of stakeholder needs and requirements (e.g., to the stakeholders, other sources, organizational strategy, and business or mission analysis results). * Provide baseline information for configuration management.
4.3	System Requirements Definition Process		Transforms the stakeholder, user-oriented view of desired capabilities into a technical view of a solution that meets the operational need of the user
	Prepare for system requirements definition	4.3.1.4.a	* Establish the approach for defining the system requirements. This includes system requirements methods, tools, and the needs for and requirements of any enabling systems, products, and services. * In conjunction with the architecture definition process, determine the system boundary, including the interfaces, that reflects the operational scenarios and expected system behaviors. This task includes identification of expected interactions of the system with systems external to the system (control) boundary as defined in negotiated interface control documents (ICDs).
	Define system requirements	4.3.1.4.b	* Identify and define the required system functions. * Identify the stakeholder requirements or organizational limitations that impose unavoidable constraints on the system and capture those constraints. * Identify the critical quality characteristics that are relevant to the system, such as safety, security, reliability, and supportability. * Identify the technical risks that need to be accounted for in the system requirements. * Specify system requirements, consistent with stakeholder requirements, functional boundaries, functions, constraints, critical performance measures, critical quality characteristics, and risks.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Analyze system requirements	4.3.1.4.c	* Analyze the integrity of the system requirements to ensure that each requirement or set of requirements possess overall integrity. * Provide analysis results to applicable stakeholders to ensure that the specified system requirements adequately reflect the stakeholder requirements. * Negotiate modifications to resolve issues identified in the requirements. * Define verification criteria—critical performance measures that enable the assessment of technical achievement. ** Include Measures of Performance (MOPs) and technical Performance Measures (TPMs), which are implementation measures of success that should be traceable to the MOEs and MOSs (operational perspective) with the relationships defined.
	Manage system requirements	4.3.1.4.d	* Ensure agreement among key stakeholders that the requirements adequately reflect the stakeholder intentions. * Establish and maintain traceability between the system requirements and the relevant elements of the system definition * Maintain throughout the system life cycle the set of system requirements together with the associated rationale, decisions, and assumptions. * Provide baseline information for configuration management.
4.4	Architecture Definition Process		Generate system architecture alternatives, to select one or more alternative(s) that frame stakeholder concerns and meet system requirements, and to express this in a set of consistent views. * Enable the creation of a global solution based on principles, concepts, and properties logically related and consistent with each other.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Prepare for architecture definition	4.4.2.1.a	* Identify and analyze relevant market, industry, stakeholder, organizational, business, operations, mission, legal, and other information that will help to understand the perspectives that will guide the development of the architecture views and models. * Analyze the system requirements and tag nonfunctional requirements, that is, those dealing with operational conditions, (e.g., safety, security, dependability, human factors, simplicity of interfaces, environmental conditions), as well as life cycle constraints (e.g., maintenance, disposal, deployment) that will strongly influence the definition of the solution elements. * Capture stakeholder concerns related to architecture. (Usually related to life cycle stages.) * Establish the approach for defining the architecture. * Ensure the enabling elements or services will be available.
	Develop architecture viewpoints	4.4.2.1.b	* Based on the identified stakeholder concerns, establish or identify the associated architecture viewpoints, the supporting kinds of models that facilitate the analysis and understanding of the viewpoint, and relevant architecture frameworks to support the development of the models and views.

INCOSE 2015 SE Handbook Section Number/Name	Sub-Section	Definitions
Develop models and views of candidate architecture	4.4.2.1.c	* Select or develop supporting modeling techniques and tools. * In conjunction with the system requirements definition process, determine the system context (i.e., how the SOI fits into the external environment) and boundary, including the interfaces, that reflect the operational scenarios and expected system behaviors. * Determine which architectural entities (e.g., ,functions, input/output flows, system elements, physical interfaces, architectural characteristics, information/ data elements, containers, nodes, links, communication resources, etc.) address the highest priority requirements (i.e., most important stakeholder concerns, critical quality characteristics, and other critical needs). * Allocate concepts, properties, characteristics, behaviors, functions, and/or constraints that are significant to architecture decisions of the system to architectural entities. * Select, adapt, or develop models of the candidate architectures of the system, such as logical and physical models. * Determine need for derived system requirements induced by necessary added architectural entities (e.g., functions, interfaces) and by structural dispositions (e.g., constraints, operational considerations). * Compose views from the models of the candidate architectures. * Develop requirements for each system element that correspond to allocation, alignment, and partitioning of architectural entities and system elements. * Analyze the architecture models and views for consistency and resolve any issues identified. * Verify and validate the models by execution or simulation, if modeling techniques and tools permit, and with traceability matrix of ConOps.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Relate the architecture to design	4.4.2.1.d	* Determine the system ***elements*** that reflect the architectural entities. * Establish allocation matrices between architectural entities using their relationships. * Perform interface definition for interfaces that are necessary for the level of detail and understanding of the architecture. * Determine the design characteristics that relate to the system elements and their architectural entities, such as by mapping (section 4.5) * Determine need for derived system requirements induced by necessary added architectural entities (e.g., functions, interfaces) and by structural dispositions (e.g., constraints, operational conditions). Use the system requirements definition process to formalize them. * For each system element that composes the parent system, develop requirements corresponding to allocation, alignment, and partitioning of architectural entities and system requirements to system elements.
	Assess architectural candidates	4.4.2.1.e	* Using the architecture evaluation criteria, assess the candidate architectures by applying the system analysis, measurement, and risk management processes. * Select the preferred architecture(s) by applying the decision management process.
	Manage the selected architecture	4.4.2.1.f	* Capture and maintain the rationale for all selections among alternatives and decision for the architecture, architecture framework(s), viewpoints, kinds of models, and models of the architecture. * Manage the maintenance and evolution of the architecture, including the architectural entities, their characteristics (e.g., technical, legal, economical, organizational, and operational entities), models and views. * Establish a means for the governance of the architecture, including roles, responsibilities, authorities, and other control functions. * Coordinate review of the architecture to achieve stakeholder agreement using stakeholder requirements and system requirements as references.
4.5	Design Definition Process		Provides sufficient detailed data and information about the system and its elements to enable the implementation consistent with architectural entities as defined in models and views of the system architecture.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Prepare for design definition	4.5.1.4.a	* Plan for technology management by identifying the technologies needed to achieve the design objectives for the system and its system elements. * Identify the applicable types of design characteristics for each system element considering the technologies that will be applied. * Define and document the design definition strategy, including the need for and requirements of any enabling systems, products, or services.
	Establish design characteristics and design enablers related to each system element	4.5.1.4.b	* Perform requirements allocation to system elements for all requirements and system elements not fully addressed in the architecture definition process. * Define the design characteristics relating to the architectural characteristics for the architectural entities, and ensure that the design characteristics are feasible. * Perform interface definition to define the interfaces that were not defined by the architecture definition process or that need to be refined as the design details evolve. * Capture the design characteristics of each system element. The resulting artifacts will be dependent on the design methods and techniques used. * Provide rationale about selection of major implementation options and enablers.
	Assess alternatives for obtaining system elements	4.5.1.4.c	* Identify existing implemented elements, including COTS, reused, or other non-developed system elements. * Assess options for the system elements, including the COTS system elements, the reused system elements, and the new system elements to be developed using selection criteria that is derived from the design characteristics. * Select the most appropriate alternatives. * If the decision is made to develop the system element, rest of the design definition process and the implementation process are used. If the decision is to buy or reuse a system element, the acquisition process may be used to obtain the system element.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Manage the design	4.5.1.4.d	* Capture and maintain the rationale for all selections among alternatives and decision for the design, architecture characteristics, design enablers, and sources of system elements. * Manage the maintenance and evolution of the design, including the alignment with the architecture. * Establish and maintain bidirectional traceability between the architecture entities (including views, models, and viewpoints) to the stakeholder requirements and concerns; system requirements and constraints; system analysis, trades, and rationale; verification criteria and results; and design elements. * Provide baseline information for configuration management. * Maintain the design baseline and the design definition strategy.
4.6	System Analysis Process		Provides a rigorous basis of data and information for technical understanding to aid decision-making across the life cycle. * Perform quantitative assessments and estimations that are based on analyses, such as cost, affordability, technical risk, feasibility, effectiveness, and other critical quality characteristics.
	Prepare for system analysis	4.6.1.4.a	* Define the scope, types, objectives, and level of accuracy of required analyses and their level of importance to the system stakeholders. * Define or select evaluation criteria (e.g., operational conditions, environmental conditions, performance, dependability, costs types, risk types). * Determine the candidate elements to be analyzed the methods an procedures to be used, and the needed justification items. * Determine the need and requirements for and obtain or acquire access to the enabling systems, products, or services necessary to perform analyses of the SOI. * Schedule the analyses according to the availability of models, engineering data (e.g., OpsCon, business models, stakeholder requirements, system requirements, design characteristics, verification actions, validation actions), skilled personnel, and procedures. * Document the corresponding system analysis strategy.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
	Perform system analysis	4.6.1.4.b	* Collect the data and inputs needed for the analysis, highlighting any assumptions. * Carry out analyses as scheduled using defined methods and procedures for cost, risk, effectiveness, and validation of assumptions. * Conduct in-process peer reviews with appropriate subject matter experts to assess the validity, quality, and consistency of the evolving system with the stakeholder objectives and with previous analyses.
	Manage system analysis	4.6.1.4.c	* Baseline the analysis results or reports using the configuration management process. * Maintain an engineering history of the system evolution from stakeholder needs definition to ultimate system retirement so that the project team can conduct bidirectional searches at any time during—or after—the system life cycle.
4.7	Implementation Process	**Fabrication of Elements**	Realizes a specified system element by creating or ***fabricating*** a system element conforming to that element's detailed description that flow from the element's requirements.
4.8	Integration Process	**Fabrication of System**	Synthesizes a set of system elements into a realized system (product or service) that satisfies system requirements, architecture, and design. * Any integration constraints are identified and considered during the definition of the requirements, architecture, and design.
4.9	Verification Process	**T&E**	Provides objective evidence that a system or system element fulfils its specified requirements and characteristics.
4.10	Transition Process	**Transition**	Establishes a capability for a system to provide services specified by stakeholder requirements in the operational environment.
4.11	Validation Process	**Assessment**	Provide objective evidence that the system, when in use, fulfills its business or mission objectives and stakeholder requirements, achieving its intended use in its intended operational environment.
4.12	Operation Process	**Operations**	Using the system to deliver its services. * Preparing for the operation of the system, supplying personnel to operate the system, and monitoring operator—system performance.

INCOSE 2015 SE Handbook Section Number/Name		Sub-Section	Definitions
4.13	Maintenance Process	**Maintenance**	Sustains the capability of the system to provide a service. * Includes activities to provide operations support, logistics, and material management. * Based on feedback of the operational environment, problems are identified, and corrective, remedial, or preventive actions are taken to restore full system capability.
4.14	Disposal Process	**Disposal**	End the existence of a system element or system for a specified intended use, appropriately handle replaced or retired elements, and to properly attend to identified critical disposal needs.

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APPENDIX B. NEAR FUTURE ROCKET SYSTEM COMPANIES INFORMATION

(1) Ariane Space Company

Ariane Space is a French company with vast experience serving the United States and Japan at its launch facilities in both South America and Central Asia. The Ariane 62 is designed to launch 5 mT payload to GEO for $15,400 per kg. The Ariane 64 heavy-lift rocket capability is designed to bring a 10 mT payload to GEO for $12,600 per kg. The timeline for these technologies are comparable to the previous two in 2020 (Smith 2016).

(2) Blue Origin

Blue Origin, founded in 2000 by Amazon CEO Jeff Bezos is working on a rocket transportation system called the New Glenn. Blue Origin claims BE-4 development will be fully funded by the private sector, saving taxpayers $2.2 billion. The BE-4 asserts 1.1 million pounds of thrust, exceeding its Russian counterpart of 860 thousand pounds of thrust, ultimately saving the taxpayer another $3 billion over 20 years of use. In 2016, ULA entered into a public-private partnership with Blue Origin for the U.S. Air Force's payloads on the Vulcan launch vehicle (United Launch Alliance 2016). The payload capacity will be 13 MT, costing $15,000-20,700 per kg to bring the payload to GEO (Smith 2016), and will be ready to launch sometime between 2019–2022. Although reusability is a goal of Blue Origin, the company has only used flight-proven rockets in the launch to the suborbital realm to date (Clark 2017).

(3) NASA SLS

The National Air and Space Administration (NASA) has designed its own rocket, as well, called the SLS Block 1A. The capability that has been designed to be reality in 2023 includes the ability to haul 70–100 MT to GEO for anywhere between $20,000–40,000 per kg (Kyle 2017).

(4) United Launch Alliance

ULA is a joint venture of the two U.S. aerospace juggernauts: Boeing and Lockheed Martin. ULA's main customer base is the government satellite community, who place a premium on the company's record of 107 consecutive successful satellite launches (Smith 2016).

ULA says that a "lower-end mission," carrying perhaps 4.75 metric tons aboard one of its Atlas V rockets costs $164 million, while launch costs across its entire fleet average $225 million (maximum payload: 8.9 tons) (Smith 2016).

Now ULA says its working on ways to lower its costs, especially with an eye to the commercial market. A planned "dual launch system," says ULA, "would launch two spacecraft on a single launch vehicle, cutting costs by 25%–40%" (Smith 2016).

(5) SpaceX

SpaceX is already one of the most economical rockets for space launch and the reusability was proven during the March 30, 2017 launch when the Falcon 9 rocket utilized a first stage that had previously delivered the SES-10 satellite to orbit in April 2016. Reusability of the first stage that costs about $30 million could bring the price down by an estimated 30% (Knapp 2017). The company proclaims that the Falcon Heavy can carry more than three times the payload than the Atlas V, and Internet pricing states that the rocket will carry 8 mT to GEO for the price of $11,250 per kg (with a new rocket, although there is anticipation of a meaningful discount when using a "flight proven" Falcon 9 rocket) when the launch vehicle is transporting its maximum delivered cargo weight (SpaceX n.d.a.).

Table 10 indicates the historical payload capacity of rocket-based systems. This data was adapted from (Skrabek n.d.).

Table 10. Past, Present, and Future Rocket Payload Capacity to LEO (in metric tons). Adapted from Skrabek (n.d.)

Rocket Name	Country/ Company	Years in Service		Total Years in Service	Mean Service Year	payload to LEO	
		Starting year	ending year			kg	mt
Black Arrow	UK	1969	1971	2	1970	135	0.135
Minotaur 1	USA	2000	2017	17	2009	580	0.58
Falcon 1	USA	2006	2009	3	2008	180	0.18
Atlas LV-3B	USA	1960	1963	3	1962	1,360	1.36
Kosmos-3M	USSR/Russia	1967	2010	43	1989	1,500	1.5
Titan II	USA	1964	1966	2	1965	3,100	3.1
N-1	Japan	1975	1982	7	1979	1,200	1.2
Delta II	USA	1989	2011	22	2000	5,089	5.089
Vostok	USSR	1960	1991	31	1976	4,725	4.725
Long March 2D	China	1992	2017	25	2005	3,500	3.5
PSLV	India	1993	2008	15	2001	3,250	3.25
Titan IIIB	USA	1966	1987	21	1977	3,300	3.3
Long March 4B	China	1999	2017	18	2008	420	0.42
Ariane I	ESA	1979	1986	7	1983	1,400	1.4
GSLV	India	2001	2017	16	2009	5,000	5
Soyuz	USSR/Russia	1966	2017	51	1992	7,100	7.1
Titan IV	USA	1989	2005	16	1997	17,000	17
Ariane V	ESA	1996	2017	21	2007	21,000	21
Atlas III	USA	2000	2005	5	2003	8,640	8.64
H-IIA	Japan	1994	2017	23	2006	10,060	10.06
Proton	USSR/Russia	1965	2017	52	1991	20,700	20.7
Space Shuttle (STS)	USA	1981	2011	30	1996	24,400	24.4
Long March 3B	China	1996	2017	21	2007	12,000	12
Ariane IV	ESA	1990	2003	13	1997	7,600	7.6
Energia	USSR	1987	1988	1	1988	88,000	88
Zenit	USSR/Russia	1985	2017	32	2001	13,740	13.74
Long March 2F	China	1999	2017	18	2008	8,400	8.4
Atlas V	USA	2002	2017	15	2010	12,500	12.5
Angara 5	France	2014	2017	3	2016	28,500	28.5
Delta IV	USA	2003	2017	14	2010	9,420	9.42
Saturn 1B	USA	1966	1975	9	1971	21,000	21
Falcon 9.1	USA/SpaceX	2013	2017	4	2015	28,000	28
Delta IV Heavy	USA	2004	2017	13	2011	28,790	28.79
N1	USSR	1969	1972	3	1971	105,000	105
Saturn V	USA	1967	1973	6	1970	127,000	127

Rocket Name	Country/ Company	Years in Service		Total Years in Service	Mean Service Year	payload to LEO	
		Starting year	ending year			kg	mt
Falcon Heavy	USA/SpaceX		2017	n/a	2017	54,400	54.4
New Glenn 2	USA/Blue Origin		2020	n/a	2020	70,000	70
New Glenn 3	USA/Blue Origin		2020	n/a	2020	100,000	100
SpaceX ITS	USA/SpaceX		2024	n/a	2024	300,000	300

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